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American Society for Testing Materials

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COLOR AND ITS MEASUREMENT

Edgar Marburg Lecture

By C. E. Kenneth Mees[1]

It is a high honor to be selected to give the Edgar Marburg memorial lecture before the annual meeting of the American Society for Testing Materials. The Edgar Marburg lectures are intended to promote the knowledge of engineering materials, and it may seem a little strange that the subject selected for such a lecture should deal merely with the external appearance of objects and not, as has generally been the case, with their essential properties; but our attitude towards the external appearance of objects has undergone a most striking change in the last few years. Until recently it was held sufficient that any given object should be capable of adequately fulfilling its functions; that it should wear well; and that it should be relatively simple to use. Today, however, the public demands that things should not only be useful but they should also be decorative, and on every side color is being employed to render the products of industry more attractive to the purchaser. The introduction of the artist into industry has resulted in the production of new designs which differ in tradition, in form, but especially in color. My purpose in this lecture commemorating the work of your late Secretary-Treasurer is to discuss the physical nature of color and the methods which can be used for its measurement and standardization.

The physical nature of color involves, of course, a consideration of the nature of light. A knowledge of light is attained through the eye, which receives the impressions from the outside universe and transforms them into nerve changes which can affect the brain.

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[1] Director of Research and Development, Eastman Kodak Co., Rochester, N. Y.

In order to identify the impressions which produce an effect on the eye, we have named them "light," and in order to form a coherent picture of what they are, we have imagined them to consist of trains of very small pressure waves in a theoretical medium which pervades all space and which is called the "ether." If we take a beam of white light and analyze it by passing it through a prism which sifts out and separates waves of different lengths—much as we might analyze a pile of dirt excavated from a quarry by passing it through a series of sieves which would put into separate piles the large rocks, the small rocks, the larger stones, the smaller stones, fine pebbles, coarse sand, fine sand and dust—then we shall find that our beam of white light is spread out into a broad beam, each section of which is differently colored, so that we get a band of colors starting with red, running through orange and yellow to green; then through blue-green to blue and violet (see Fig. 1). Just as by knowing the size of the openings in the sieves we could tell the average size of the particles into which our dirt would have been divided, so we can calculate the length of the waves of light which correspond to each of the colors of this band.

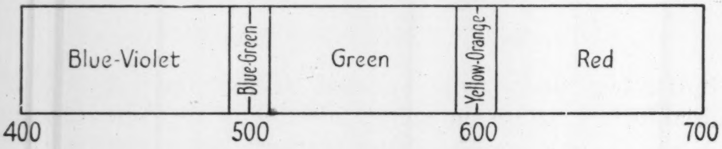

FIG. 1.—Diagram of Spectrum.

The units used are very small ones. A millimeter is about a twenty-fifth of an inch, so that one-thousandth of a millimeter, a micron, is about one twenty-five-thousandths of an inch; and if you use one thousandth of a micron as the unit, then the length of the wave of the deepest red light that you can see is about seven hundred units and the deepest violet which can be recognized by the eye about four hundred units. Shorter waves of light than those of the violet waves—only two hundred or three hundred units long—are known to exist and can be detected by their action upon photographic materials. Although they cannot be seen, these waves out beyond the violet are commonly referred to as "ultra-violet light."

Now, suppose we pass our beam of white light through a piece of colored gelatine, so that instead of having a beam of white light, we have a beam of pink light, then we can see that this light differs in some way from the white light which we originally had. If we analyze it as we did the white light, we shall find that in our band of colors some of the green light is missing (see Fig. 2), showing that the impression of color on the eye was produced not by the addition of anything to the beam of white light, but by the removal of some of its constituents by the colored gelatine. This is called "absorption" and the portion removed is called "the characteristic absorption band" of the color. In the same way, instead of letting a beam of light fall on a whitened wall, we may let the beam of white light fall on a piece of pink paper, the patch appearing pink instead of white. Now, if we analyze the beam of white light, so that the analyzed band or "spectrum," as it is called, falls on the colored paper, we shall see that some of its components appear to be missing, just as they would have been if we had put a colored gelatine filter in the path of the beam. The pink paper reflects the red and also the blue light, but in the middle of the green it has a strong absorption band removing that constituent. We shall be justified, therefore, in stating that a colored object appears colored because it absorbs some wave lengths of light to a greater extent than others, and that there will be an intimate relation between the absorption band of the substance and the color which it appears to the eye.

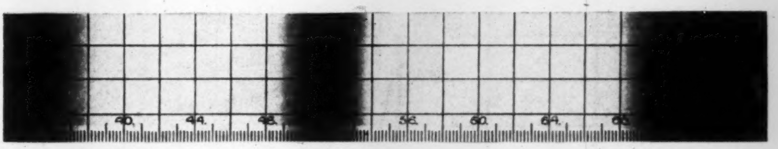

FIG. 2.—Absorption Spectrum of Red Dye.

We will now proceed to examine what this relation will be. Suppose that we place an opaque object in our spectrum so that part of the light is cut off, then we have artificially introduced an absorption band into the spectrum of the light which we are projecting, and if we recombine the light of the spectrum we shall get colored light, the color depending on the position of the absorption band in the spectrum. As it is inconvenient to continually shift from the spectrum to the combined beam of light, a convenient way of showing this is to put a little glass prism into the spectrum, so that the portion of the light which passes through it is deviated upwards. Then when we recombine the spectrum, the upper patch represents the portion which would be represented if an opaque medium were there, and the lower circle shows the color which results from this localized absorption of part of the spectrum.

When the absorption band is in the extreme red, the color obtained is a very light blue, and as the band passes into the orange, the color becomes a more pronounced blue, until when the band is in the yellow part of the spectrum, the color is almost violet; so that we see that a light blue color is produced by an absorption of the extreme red, a stronger blue by absorption farther into the red, and a violet by an absorption of the yellow. As the band moves into the yellow-green, the violet changes rapidly to a magenta, which persists as the band moves through the green, finally becoming a pink, and then, as the band shifts into the blue-green, the pink changes to an orange; as the band goes into the blue, to a yellow; and finally when the absorption band occupies its last position in the extreme violet, the color of the absorption patch is a light lemon yellow. We see from this that if we imagine a single absorption band to pass down the whole spectrum, the changes run from light sky blue, through violet-blue, purple, magenta, pink, orange, yellow, to lemon yellow. These colors may be termed the "residual" colors, as they are those produced by the loss of a single sharp portion of the spectrum, and by their aid the absorption band corresponding to almost any natural colored object can be remembered.

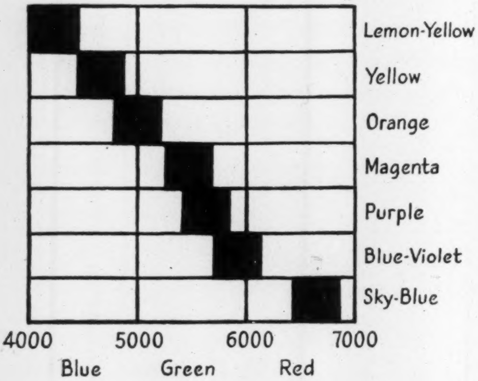

FIG. 3.—Chart of Residual Colors.

There is one common class of colors, however, that is not represented among these residual colors, and this comprises the greens. To produce a green, all that is necessary is to absorb from a sky blue the violet end of the spectrum; that is, a green is produced by two absorption bands, one at the red end and the other at the blue end of the spectrum. In a bluish green the red absorption band is strong, the blue absorption band weak; and in a yellow-green the blue absorption band is strong and the red absorption band is weaker.

Figure 3 shows the residual colors in a graphic form. It must not be imagined, however, that the absorption bands of natural colors are as complete and sharp-edged as those which produce the colors which I have shown. Actual absorption bands are almost always more or less gradual, though those of red, yellow, and orange objects are frequently fairly sharp. Green and blue colors, however, are by no means so sharp. Figure 4 illustrates fairly well the theoretical and the actual absorption of an (*a*) average violet and (*b*) a green color.

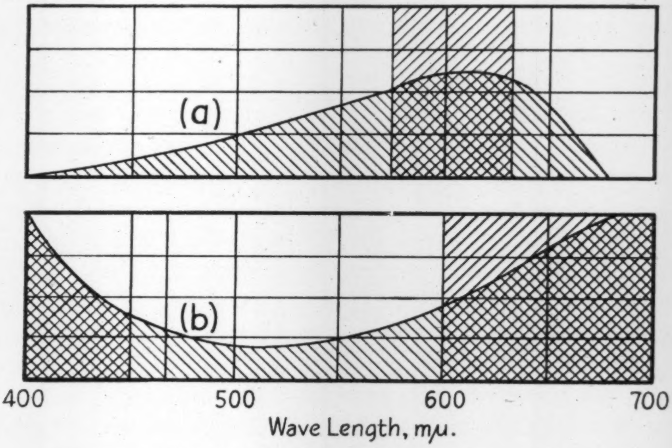

FIG. 4.—Theoretical and Actual Absorptions of Violet.

Now, having clearly in our minds the definition of a colored object—namely, that a colored object is one which absorbs wave lengths selectively, so that the spectrum shows an absorption band in it—let us consider the nature of these bands in the case of the chief primary colors. A mere glance at the spectrum will show that it is divided into three main regions, shading into one another, it is true, but still clearly distinguishable. These three chief colors are the red region, the green region, and the blue region. Yellow, which is such a common color in everyday life, occupies only a very small portion of the spectrum, while the purples and magentas are entirely absent from it. Now, our list of residual colors did not contain these spectral colors. In the list of residuals there is no pure red, no green, and no pure blue-violet, the violet of the residual colors being a purplish violet with red in it. The reason that these colors are not contained in the residuals is that they occur not by absorption of a small portion from the spectrum, but by the absorption of two-thirds of the spectrum for each of the colors and the transmission or reflection of the remaining one-third. Thus, if we absorb all the blue and all the green, we get a pure strong red, and if we absorb all the red and all the blue and violet, we get a pure strong green, while if we absorb all the red and all the green we get only the blue-violet left. These three colors then—red, green, and blue-violet—are entitled to be called the "primary colors," and this the more because the eye has apparently three separate color sensations sensitive to these primary colors.

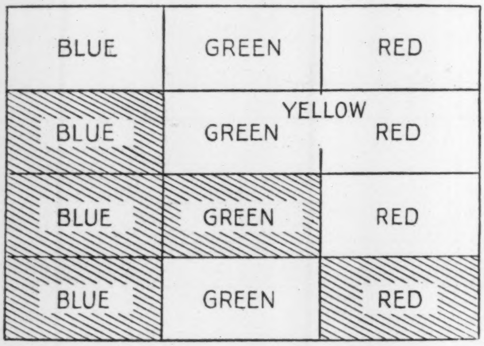

FIG. 5.—Chart of Primary Colors.

If we place a broad absorption band in the spectrum so as to cut out each of these three primary colors in turn, we get three other colors which occurred among our residuals, each of them corresponding to one of the primaries. When we cut out the red, we get a strong blue-green containing all the green and blue-violet light mixed together. This color is a kind of pale blue, which is generally known among workers in color as "minus red," because it consists of white light which has entirely lost its red. When we absorb all the green from the spectrum, we get a strong magenta color, which we may similarly term "minus green," and when we absorb all the blue and violet from the spectrum, we get a very bright yellow patch, showing that yellow, which is one of the commonest colors in nature, is due simply to an absence of blue, yellow being "minus blue," so that if you had a beam of yellow light and added blue light to it, you would get white light.

The three colors—blue-green, magenta, and yellow—are the inverse or complementary colors to the primary red, green, and blue colors, and if we have three color films transmitting these three colors, by superposition in pairs we shall generate the primary colors (Fig. 5). Thus the yellow filter absorbs blue-violet and transmits red and green, the magenta filter absorbs green and transmits red and blue. If we place the magenta filter over the yellow filter, the magenta one absorbs the green, the yellow one absorbs the blue, and only the primary red is transmitted. Similarly, when we place the blue-green one over the yellow, the blue-green one absorbs the red; the yellow one, the blue; and only primary green is transmitted; while, finally, if we place the blue-green over the magenta, the blue-green filter absorbs the red; the magenta, the green; and only primary blue is transmitted. If all three colors are superposed, since each absorbs one of the three primary colors, no light is transmitted and the three together are opaque.

Among artists, and, in fact, in the eyes of the general public, the primary colors are commonly considered to be red, blue, and yellow, the red in question being a madder transmitting blue, and the blue a cobalt transmitting or reflecting a large amount of green. It will be evident that these colors are identical with our three complementary colors—yellow, blue-green and magenta—and the reason that these are considered to be primary is obvious when it is realized that the colors in question are in the form of pigments and that the mixing of the pigments is nearly equivalent to the superposition of our colored films. Thus, when we mix a cobalt blue with a yellow pigment, the yellow absorbs the blue-violet primary, and the cobalt the red, leaving only the green light to be reflected. If, however, instead of mixing pigments we mix colored lights, we shall at once realize how truly red, green, and blue are the primary colors. A lantern may be arranged so that its projection lens is divided into three parts, over which are placed three colored filters. Now, if red be projected through the top lens, green through the middle, and blue through the bottom, we shall get a white patch on the screen. If the blue light is cut off, the mixture of red and green will be yellow; if only the red and blue are projected, magenta results; and if only green and blue, a blue-green color is obtained. Green cannot be obtained by mixing blue and yellow lights; if only two lenses be used —one projecting blue light and the other yellow—not green but white results; green is obtained from yellow light not by the addition of anything to it, but by the subtraction of its red component, which can, of course, be accomplished by the use of a blue pigment which absorbs red.

The measurement of the color of objects can be accomplished by two methods: The analytical method, in which the color is split up into its component parts by means of a spectroscope; and the synthetic method, in which the color is matched in its appearance to the eye by mixing colors of known composition. It will be seen that these two methods really measure different things. The analytical method measures the stimulus, which produces the sensation of color, and its results are expressed in terms of physical units. The synthetic method measures the sensation which the color produces upon the observer, and while colors which are due to the same composition of light, that is, to the same stimulus, are always the same in their effect on the eye, the converse is not true, and quite different stimuli may produce the same sensation. Thus, a sodium flame appears to the observer a bright yellow color and a dandelion also appears a bright yellow color, approximating very closely in appearance that of the sodium flame, so that if the light of a sodium flame and sunlight reflected from a dandelion are allowed to fall in juxtaposition upon a sheet of white paper, the colors can be almost exactly matched. Nevertheless, these two colors are quite distinct when analyzed in a spectroscope, the sodium flame showing only a single monochromatic ray of light in the spectroscope, while the dandelion reflects almost the entire spectrum, absorbing only the blue.

The analytical instrument used in studying the light is the "spectroscope," but the quantitative measurement of color is undertaken by means of an instrument termed the "spectrophotometer," which is essentially a spectroscope with photometric attachments. In this instrument, any portion of the spectrum can be isolated and divided into two portions having the same color and adjacent to one another. Into one of the beams is introduced the colored object to be measured, which produces an absorption of the spectral region in question. The other beam is then darkened by some photometric means until the two patches, as seen through the eyepiece of the instrument, appear of equal intensity. Since the amount of darkening which has been introduced photometrically is known and is equal to the amount which has been caused by the absorption of the colored object, we can read from the instrument the quantitative value of the absorption at any point of the spectrum. This is repeated throughout the spectrum, step by step, and a curve of absorption against the wave length of the spectrum is obtained; thus, if we have a red dye solution, we shall obtain a curve similar to that shown in Fig. 6. The abscissae of the curve represent wave lengths of light, and the ordinates represent the absorption in units inversely proportional to the thickness of the solution which will produce a transmission of one-tenth of the original intensity. It will be seen that the red dye has a slight absorption in the blue, rising very rapidly to a strong maximum in the green at a wave length of about 520, and falling off again until, at a wave length of 600, it is transmitting almost all the light.

The readings of the spectrophotometer are directly proportional to the concentration of the dye solution, and it can thus be used for measuring the concentration of a dye of unknown strength. All that is required for this analysis is a standard sample of dye which is known to be pure. A solution of known strength is made from this standard, a solution of the sample to be analyzed of the same nominal concentration is prepared, the two solutions are read on the spectrophotometer, and the absorption coefficients obtained on the instrument are compared. The concentrations of the dyes are in the same proportion as their absorption coefficients.

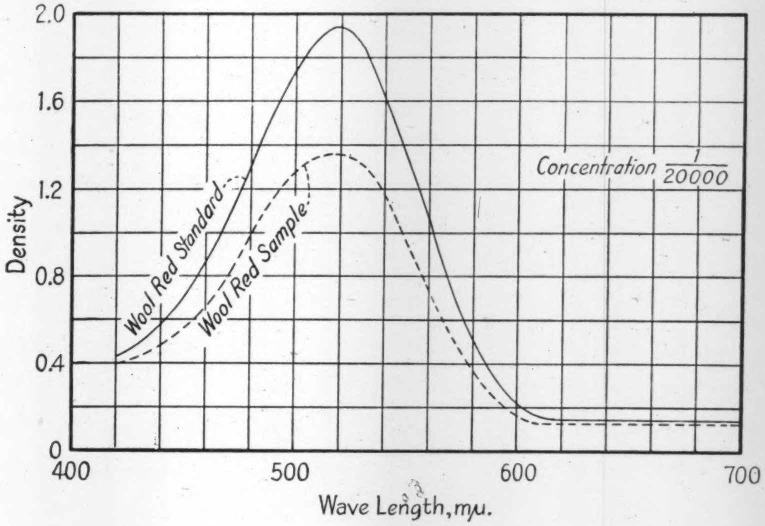

FIG. 6.—Spectral Absorption Curve for Red Dye.

Recently, other spectrophotometers have been put on the market for studying the color of the light reflected from colored objects, and these are often known as "color analyzers." An instrument of this type, for instance, is made by Keuffel & Esser. A very ingenious, modified spectrophotometer has been developed by Prof. Arthur C.

Hardy of the Massachusetts Institute of Technology in collaboration with the research laboratory of the General Electric Co. In this instrument, the color is analyzed by means of a prism and the brightness of the light reflected from the object to be tested is compared for each wave length with that of a sample of standard white material by means of a photo-electric cell; the current from this cell, suitably amplified, is used to drive a motor which controls the position of a recording pen so that the instrument automatically draws the curve of reflection of the object. Several of these curves are shown in Fig. 7.

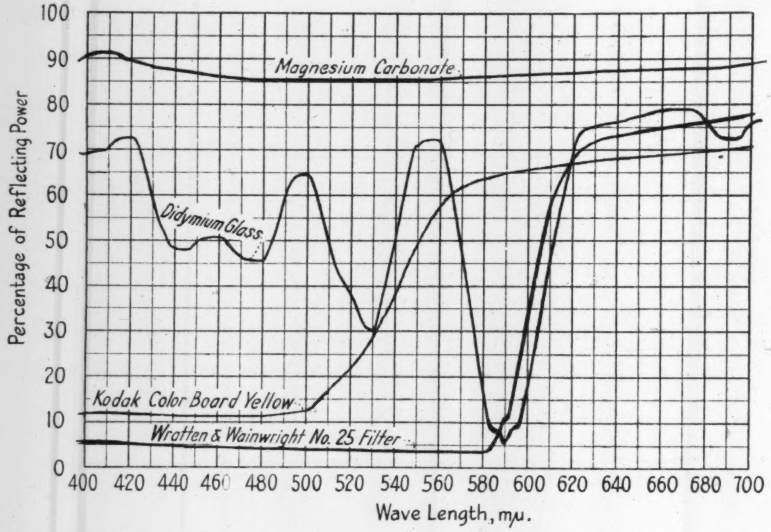

FIG. 7.—Curves from Automatic Spectrophotometer.

In the synthetic method of measuring color, the color of the object to be measured is matched by mixing colors of known composition or colors which are taken as standards, and the color to be measured is then expressed in terms of the proportion of the known standard colors required to match it. Such instruments are known as "colorimeters" and they have the advantage over the spectrophotometer that the statement of the composition of a color as expressed by a colorimeter enables one to form immediately an idea of the appearance of the color, while the spectrophotometric curve does not give any direct indication of the color of an object. If we know the spectrophotometric reflection curve of a given paper, the visibility curve of the eye, and the energy curve of the light falling on the paper, it is possible to calculate the resulting color, but the calculation is by no means simple, and for the practical control of colored objects in industry, colorimetric methods are generally adopted.

I would interpolate here a remark with regard to the word "colorimeter." It is unfortunate that the word colorimeter has been applied to two totally different instruments. The colorimeter used in chemical analysis does not measure color. It is an instrument in which the color of a given solution is matched by that of a solution of known composition, and it is used for determining the quantity of colored substance in a solution and not for measuring the color. The term colorimeter should naturally be restricted to instruments which are used for measuring color itself, and some other name should be applied to the instrument used by the chemist. Until that is done, there will always be some confusion between these two distinct forms of instrument.

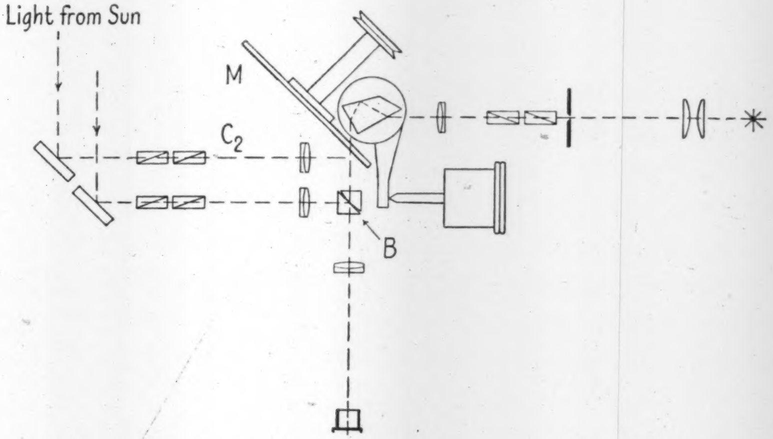

FIG. 8.—Diagram of Monochromatic Analyzer.

The sensation produced upon the eye by an object has three attributes: the brilliance, dependent upon the intensity of the light; the hue; and the saturation, that is, the proportion of white light mixed with the dominant hue. All these components are capable of change independently. Thus, starting at the red end of the spectrum, we may have a red, an orange, a yellow, a green, a green-blue, a blue, or violet color, these terms giving the approximate hue. Any of them may be diluted with white, so that we may get pale colors of each hue in turn. Moreover, we may have the group of colors which is not included in the spectrum—the purples, violets, and magentas—which are complementary to the greens of the spectrum. These may be specified most conveniently by the hue to which they are complementary.

The easiest method of specifying hue is by means of the wave length in the spectrum which corresponds to the hue in question. Thus, we may specify a red as having a hue of which the wave length is 656, corresponding in hue to the color of the red hydrogen line. A yellow might be of dominant hue 580; 570 would be a greenish yellow; 560 would be a yellowish green.

The measurement of hue and saturation can be made by means of the "monochromatic analyzer." In this instrument the color to be measured is balanced by means of a mixture of a monochromatic spectral color and white light. Thus, in order to measure a green tinted paper, we place the paper so that the light reflected from it falls into the colorimeter. In the photometric field at *B*, Fig. 8, we see one part of the field filled by the green light from the colored paper. The other part of the field can be illuminated by means of a very narrow portion of a spectrum to which can be added any proportion of white light that is required. We change the wave length of the spectral light by means of the drum until the hue appears approximately right. We next add white light from the beam C_2, reflected from the glass surface *M*, until an approximate match is obtained, keeping the intensity of the two fields the same. The hue

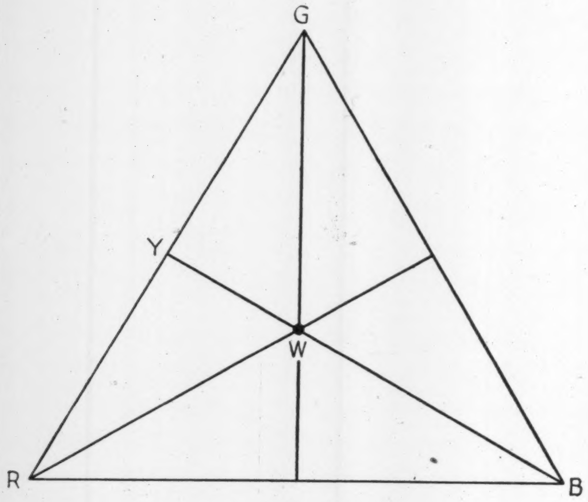

FIG. 9.—Color Triangle.

may now require a little correction, and when this is almost exactly right, the admixed white may require another correction. By this method, very rapidly used after a little practice, the color is matched exactly by the other field. The dominant hue is now read off directly from the spectral drum, and the percentage of admixed white light measured photometrically in the instrument. This is the only form of colorimeter which reads the color directly in absolute units, namely, the wave length of the dominant hue and the percentage.

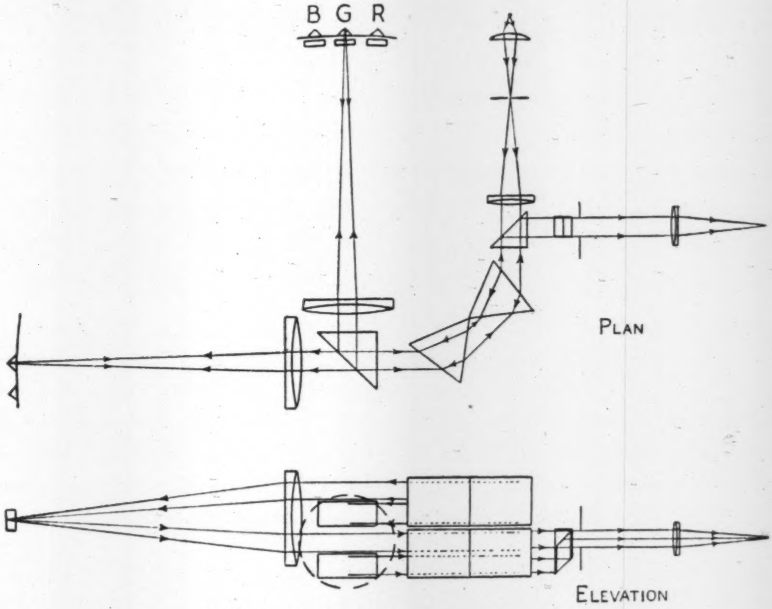

FIG. 10.—Diagram of Trichromatic Spectral Colorimeter.

Another form of colorimeter which is more commonly used and in some ways is more convenient depends upon the fact that any color can be matched by mixtures of the three primary colors if these are particularly selected for hue and are of high saturation. If we make a diagram in the form of a triangle in which the three primary colors adopted are at the apexes of the triangle, all the colors will fall somewhere in this triangle (see Fig. 9). Thus, a pure red matching the primary red will correspond to the point marked *R*. A pure green matching the primary green will correspond to the point marked *G*. As we obtain mixtures of red and green, adding the green light to the red, we travel down the line *RG*. Similarly, additions of blue to green travel along the line *GB*, and additions of blue to red along the line *RB*. When we use three colors, we travel into the triangle itself; thus, we may add green to red and travel along the line *RG* until we meet the point *Y* representing yellow and then add blue to this, and the color loses saturation and becomes whiter as it travels out into the triangle, the point which corresponds to a true visual white being represented at the point *W*.

A trichromatic colorimeter is an instrument in which this operation can be performed quantitatively. The three primary colors are selected from a spectrum, the amount being adjusted, for instance, by modifying the width of the three slits through which small portions of the spectrum pass (Fig. 10). The instrument is usually adjusted so that a white is represented by equal proportions of the three colors. White can be stated, for instance, to be 100-100-100. A pure yellow containing no blue at all will be 100-100-0, the red and green slits being wide open and the blue slit closed. Most colors will, however, have all three components in them.

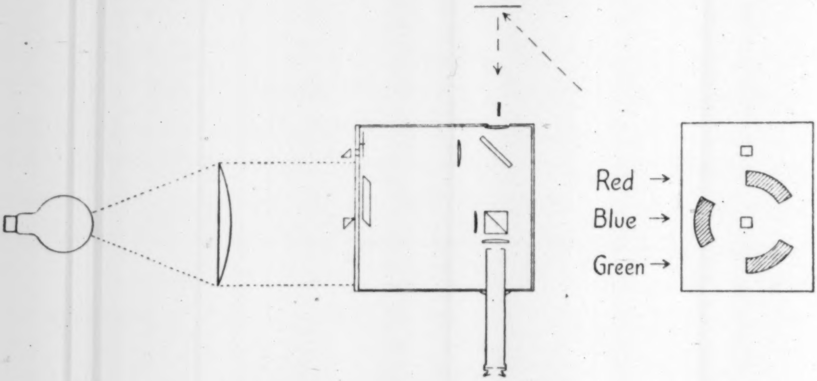

FIG. 11.—Diagram of Guild Colorimeter.

In practical instruments it is generally inconvenient to use a spectrum for the analysis, and for practical purposes it can be replaced by the colors transmitted through three properly selected filters; a number of trichromatic instruments using such filters have been built for practical purposes (Fig. 11).

A simple instrument of another type which is very suitable for works use has been designed by Mr. L. A. Jones of our laboratory (Figs. 12 and 13). It has the advantage of not requiring a spectrum or any special mixing device and of being very robust in its construction. It is based on the subtractive principle, depending upon the use of colored wedges, each wedge absorbing one-third of the spectrum, so that the three wedges are yellow, blue-green, and magenta in color, the yellow wedge absorbing the blue of the spectrum, so that it may be called "minus blue;" the magenta absorbing the green of the spectrum, so that it may be called "minus green;" and the blue or "minus red" wedge absorbing the red of the spectrum. When these wedges are placed over each other in pairs, they will give any color possible, provided that the intensity is adjusted at the same time by the use of a neutral gray wedge, which is supplied as the fourth wedge of the instrument. The instrument can be made with a number of attachments, according to the purpose for which it is required.

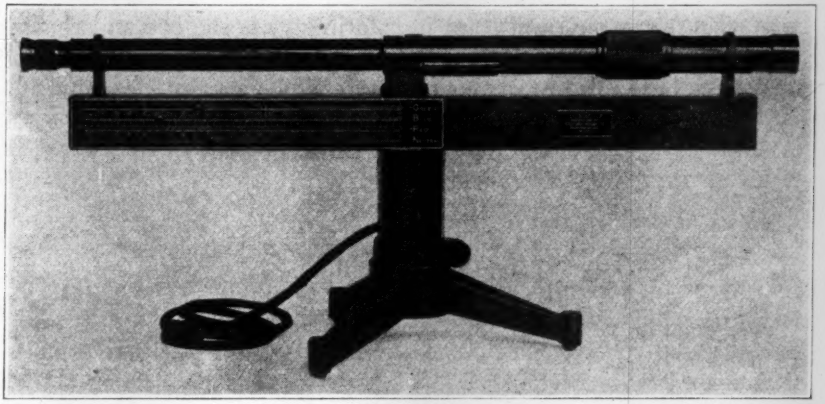

FIG. 12.—Jones Colorimeter.

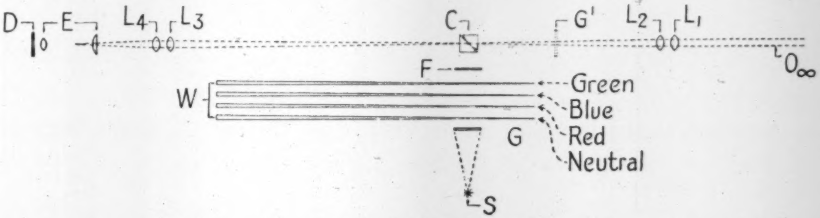

FIG. 13.—Diagram of Jones Colorimeter.

Thus, colored solutions, colored glasses, or colored papers can be measured by suitable attachments. An objection to this instrument is that it is very difficult to stabilize the colored dyes used in making the wedges; permanency in the minus red wedge especially is hard to obtain. While the instrument has been used with considerable success, the production and calibration of the wedges represent a serious difficulty in its manufacture.

One great problem in colorimetry as applied to industry is the measurement of very faint colors. In many industries the goods produced are only slightly colored, and yet this slight color has very great commercial importance. Papers, for instance, are approximately white, but a customer who has been using a slightly creamish paper will not accept one which is slightly bluish. It must always be remembered that the criterion of color in colorimetry is the eye and that no colorimeter is more sensitive than the eye to small differences in color. Differences in the hue of papers therefore which are not clearly visible to the eye cannot be made more visible by the use of a colorimeter. All that the colorimeter can do is to measure quantitative differences which are visible. This has been overcome to some extent by what is known as a "tint intensifying attachment." This was first designed by Dr. A. H. Pfund, and a convenient form was designed by Mr. L. A. Jones and is shown in Fig. 14; in this the light from the lamps used as the light source is reflected several times from the tint to be measured, the actual number of reflections in the form shown being equivalent on the average to 3. In this way, slight tints which are scarcely visible to the eye can be multiplied and measured in the colorimeter. Instruments of this type have been used successfully for the measurement of papers and such materials as alkalies.

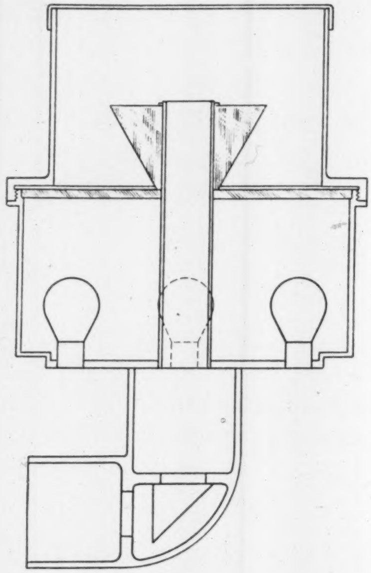

FIG. 14.—Diagram of Tint Intensifying Attachment for Jones Colorimeter.

The commercial use of colorimetry is still in its infancy, and it still presents serious difficulties. The application of colorimetric methods to each industrial problem generally requires a special study, and there is at present a dearth of industrial scientific men qualified to undertake this work. Nevertheless, the standardization of color is of an importance which increases daily. The purchasers of colored goods are insisting more and more on stability, constancy, and repeatability of color.

In this lecture, I have been able to do no more than indicate the principles of the subject, but I am convinced that within a few years the measurement of color, both analytically by means of the spectrophotometer and synthetically by means of various forms of colorimeters, will increase and will form by no means a negligible part of the work of laboratories devoted to the testing of materials.

Acknowledgment.—Acknowledgement is hereby made to Mr. W. D. Wright for Fig. 10, taken from his paper on "A Trichromatic Colorimeter with Spectral Primaries;"[1] and to Mr. J. Guild for Fig. 11, taken from his paper on "A Trichromatic Colorimeter Suitable for Standardization Work."[2]

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[1] *Transactions*, Optical Soc., Vol. 28, p. 225 (1927–1928).

[2] *Transactions*, Optical Soc., Vol. 27, p. 106 (1925–1926).

SYMPOSIUM ON AIRCRAFT MATERIALS

INTRODUCTION

BY HORACE C. KNERR[1]

A new industry is becoming established in America. Last year it represented a total investment in the neighborhood of $700,000,000. More than 6000 commercial and military planes, with a total value of over $44,000,000 were manufactured. The production of aircraft engines exceeded 7000 for the year, valued at $26,000,000. American airplanes in 1929 flew nearly 200,000,000 miles.[2]

Aircraft, including airplanes, seaplanes, flying boats, amphibians, airships and dirigibles, large and small, and recently gliders, are taking a place of rapidly increasing importance in our civilization. Ships of the air are becoming indispensable in military service, mail, express and passenger transportation, agriculture, mapping, forest patrol, exploration, travel for business and pleasure and even in sports.

There is perhaps no industry in which an exact knowledge of the properties of materials of construction is more necessary. Each individual part must be completely dependable and yet must be reduced to the lowest possible weight. Factors of safety must be ample, but factors of ignorance negligible. It is essential to know just what service each type and class of material can be depended upon to render, and to insure that each unit and element will perform at par. This calls for accurate and complete engineering data, adequate and standardized specifications, and rigorous and thorough testing to insure that requirements are met.

As the purpose of this Society is "the promotion of knowledge of the materials of engineering and the standardization of specifications and methods of testing," it is obvious that the interests and objects of the Society and of the aircraft industry are mutual.

In connection with the Society's last annual meeting it was suggested[3] that special attention be given to aircraft materials. As a result it was decided to devote two sessions of the present annual meeting to a symposium on this subject. An Advisory Committee was appointed to assist in arranging the program and in securing authors for the desired papers and also in reviewing and editing the manuscripts. The selection of the committee was based upon an effort to represent broadly various engineering phases of the industry, including military and civil departments of the Government, research foundations, educational institutions, and manufacturers of aircraft, engines and materials. The personnel of the committee was as follows:

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[1] Consulting Metallurgical Engineer; and President, Metallurgical Laboratories, Inc., Philadelphia, Pa.

[2] Aeronautical Chamber of Commerce Year Book, 1930.

[3] By Mr. H. S. Rawdon, U. S. Bureau of Standards.

Dr. R. S. Archer, Director of Research, Aluminum Company of America, Cleveland, Ohio.
Mr. Harold A. Backus, Materials Engineer, Berliner-Joyce Co., Baltimore, Md.
Mr. J. B. Johnson, Chief, Material Section, Air Corps, Wright Field, Dayton, Ohio.
Dr. Alexander Klemin, Consulting Engineer, School of Aeronautics, New York University, representing Guggenheim Foundation.
Dr. G. W. Lewis, Washington, D. C., representing the National Advisory Committee for Aeronautics.
Dr. J. A. Mathews, Vice-President and Metallurgist, Crucible Steel Co. of America, New York City.
Mr. R. R. Moore, Metallurgist, Wright Aeronautical Corp., Paterson, N. J.
Dr. J. S. Newell, Massachusetts Institute of Technology.
Dr. H. S. Rawdon, Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.
Capt. H. C. Richardson, Director of Engineering, Great Lakes Aircraft Corp., Cleveland, Ohio.
Mr. E. P. Warner, Editor, *Aviation*, McGraw-Hill Publishing Co., Inc.
Commander R. D. Weyerbacher, Manager, Naval Aircraft Factory, U. S. Navy Yard, Philadelphia, Pa.
Mr. H. L. Whittemore, Chief, Engineering Mechanics Section, VI-5, U. S. Bureau of Standards, Washington, D. C.
Mr. T. P. Wright, Chief Engineer, Curtiss Aeroplane and Motor Corp., Garden City, L. I., N. Y.
Major Clarence E. Young, Chief, Aeronautics Branch, U. S. Dept. of Commerce, Washington, D. C.
Horace C. Knerr, Chairman, Consulting Metallurgical Engineer; President, Metallurgical Laboratories, Inc., Philadelphia, Pa.

In view of limitations of space available for publication it was the consensus of opinion that the Symposium might best take the form of a group of papers each dealing with some topic of major importance in connection with aircraft materials and that these papers be in the nature of comprehensive but condensed digests and summaries rather than dealing with new or specialized developments in the art. Furthermore, it was intended that these papers be devoted to materials and testing problems rather than to design features.

It was hoped in this compendium to contribute to the aircraft industry a small reference volume of authentic information of timely and reasonably permanent value—in so far as anything may be permanent in an art which is passing through such rapid evolution.

FERROUS METALS USED IN AIRPLANE CONSTRUCTION

By J. B. Johnson[1]

Synopsis

The aircraft industry has been guided by the application of materials in other fields of engineering and has changed specifications only where it has been found that no products were available which would meet the peculiar demands of the industry. This paper covers briefly the various types of ferrous metals which have become standardized due to the cooperation between the national engineering societies, government bureaus and the industry in attempting to limit the number of steels to a minimum. The chemical content and physical properties of the several types have been tabulated with a brief summary of principal application.

The ferrous metals used in airplane construction nearly all have been adopted from standards which have been established for other types of automotive vehicles. Airplane parts are designed from materials selected for maximum strength and resilience and resistance to shock and fatigue, with minimum weight always in the foreground.

The ferrous metals can conveniently be divided into two classes: cast and wrought. These can be subdivided into the various forms in which they are actually applied.

Cast Iron and Cast Steel

Cast iron and cast steel have only a limited application in aircraft construction since the strength-weight ratio is lower than for other forms of ferrous metals. They are used, however, for their inherent advantages of economical production in complicated forms and resistance to abrasion.

The only application of cast iron is in the tail skid shoe. This is a detachable member which bears the brunt of the wear due to dragging the tail skid over the ground. A chilled cast iron of the approximate analysis shown in Table I has proved satisfactory. The depth and composition of chill is important. The former should not be less than $\frac{3}{8}$ in. and the structure should conform to a white iron with no free ferrite. Various grades of cast-iron welding rod have been used in order to build up a hard surface on a softer base, either cast iron or cast steel. Analyses of two types of welding rod are given in Table I. Good results have been obtained, but the cost of the material and its application must be balanced against the cheapness of cast iron.

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[1] Chief, Material Section, Materiel Division, Air Corps, U. S. A., Wright Field, Dayton, Ohio.

Cast steel is used for a few fittings on the landing gear and tail skid and for tail skid shoes. A medium-carbon-steel casting—Table I—has been quite generally adopted. It has good welding qualities. Alloy-steel castings have not been used to any extent up to the present time, but the air-hardening type may find a useful field since the strength per unit volume is quite high. Manganese-steel castings for tail skid shoes have not shown any particular advantage, probably due to the fact that the surface pressure is not sufficient to cold work the metal.

TABLE I.—CAST FERROUS METALS.

Material	Average Chemical Composition								Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
	Total Carbon, per cent	Manganese, per cent	Sulfur, per cent	Phosphorus, per cent	Silicon, per cent	Nickel, per cent	Tungsten, per cent	Chromium, per cent				
Chilled Cast Iron	3.50	0.50	0.08	0.50	1.80	....	....	....	....	....	....	....
Cast Steel.......	0.45	0.50	0.06 (max.)	0.05 (max.)	0.40 (max.)	....	....	....	70 000	31 500	20	30
Cast Welding Rods for Tail Skids.......	3.5	10.0	....	....	2.0 (max.)	3.0	....	3.0	....	....	....	....
	4.0	6.0	....	....	1.0	....	....	30.0	....	....	....	....
	3.5	0.2	....	....	0.5	....	16.0	10.0	....	....	....	....

RODS, BARS AND BILLETS

The airplane industry has standardized on the chemical compositions as adopted by the Society of Automotive Engineers, although in some cases with slight modifications.

Bars are specified hot rolled and annealed or annealed with a bright finish obtained by cold rolling or drawing. The hot-finished bars are generally used for drop forgings and parts which require considerable machining. Bars for this purpose are made from chipped and pickled billets and are carefully inspected for seams, laps and other surface defects. Drop forgings have not been very extensively used for fittings on account of the limited production. Propeller hubs and gears have been used in sufficient quantities to warrant the cost of forging dies. These parts are all heat-treated after forging, and the properties listed in Table II represent the finished parts.

Cold-finished bars are used for a large variety of special machined parts. It is desirable that the bars have a composition and structure which will permit heating to the normalizing temperature and cooling in air, without a reduction in tensile strength below the require-

TABLE II.—RODS, BARS AND BILLETS FOR DROP FORGINGS AND MACHINED PARTS.

Designation		Chemical Composition							Physical Properties				Uses
		Carbon, per cent	Manganese, per cent	Sulfur, per cent, max.	Phosphorus, per cent, max.	Nickel, per cent	Chromium, per cent	Other Elements, per cent	Tensile Strength, lb. per sq. in., min.	Yield Point, lb. per sq. in., min.	Elongation in 2 in., per cent, min.	Other Tests	
Low Carbon....	S.A.E. No. 1015	0.10 to 0.20	0.30 to 0.60	0.050	0.045	....	....	....	50 000[c]	36 000	....	Normality Test; Hardness	Carburized gears and shafts
Mild Carbon....	S.A.E. No. 1025	0.20 to 0.30	0.50 to 0.80	0.050	0.045	....	....	....	55 000[a]	36 000	22[a]	Bend 180 deg., mandrel twice thickness	Fittings, nuts, screw machine parts
Half-Hard Carbon	S.A.E. No. 1045	0.40 to 0.50	0.50 to 0.80	0.050	0.045	....	....	....	100 000[b]	60 000	15	Hardness	Hub flanges, small forgings, tie rods
High Carbon....	S.A.E. No. 1095	0.90 to 1.05	0.25 to 0.50	0.050	0.040	....	....	....	....	....	....	Hardness	Pins and keys, bearing plates
Nickel 3½ per cent	S.A.E. No. 2320	0.15 to 0.25	0.50 to 0.80	0.050	0.040	3.25 to 3.75	....	....	75 000[c]	....	....	Bend 180 deg., mandrel once thickness	Carburized gears
Nickel 3½ per cent	S.A.E. No. 2330	0.25 to 0.35	0.50 to 0.80	0.050	0.040	3.25 to 3.75	....	....	125 000[b]	90 000	15	Bend 180 deg., mandrel once thickness	Bolts, tension members, gears
Chrome-Nickel..	S.A.E. No. 3130	0.35 to 0.45	0.50 to 0.80	0.045	0.040	1.00 to 1.50	0.45 to 0.75	....	135 000	115 000	17.5	Hardness...........	Forgings and bolts
Chrome-Nickel..	S.A.E. No. 3250	0.45 to 0.55	0.30 to 0.60	0.040	0.040	1.50 to 2.00	0.90 to 1.25	....	200 000	160 000	12	Hardness...........	Gears
Chrome-Nickel..	.....	0.10 to 0.25	0.20 to 0.60	0.040	0.040	7.0 to 10.0	17.0 to 20.0	Silicon 0.10 to 0.70	105 000	55 000	35	Bend 180 deg., mandrel once thickness	Non-magnetic tie rods, screw machine parts, corrosion resistant parts
Chromium......	.....	0.30 to 0.35	0.65 to 0.80	0.045	0.040	....	0.90 to 1.10	....	....	....	....	....	Forgings, machined fittings
Chromium	.....	0.30 to 0.40	0.50 (max.)	0.035	0.035	....	11.5 to 15.0	Silicon 0.50 (max.)	180 000	140 000	12	Hardness...........	Corrosion resistant pins, nuts, fittings
Chrome-Molybdenum	S.A.E. No. 4130x	0.25 to 0.35	0.40 to 0.70	0.045	0.040	....	0.80 to 1.10	Molybdenum 0.15 to 0.25	125 000[b]	100 000	18	Bend 180 deg., mandrel once thickness	Forgings, machined parts
Chrome-Vanadium	S.A.E. No. 6115	0.10 to 0.20	0.30 to 0.60	0.040	0.040	....	0.80 to 1.10	Vanadium 0.15 to 0.25	80 000[c]	....	....	Hardness...........	Carburized gears and shafts
Chrome-Vanadium	S.A.E. No. 6135	0.30 to 0.40	0.50 to 0.80	0.040	0.040	....	0.80 to 1.10	Vanadium 0.15 to 0.25	135 000[b]	115 000	12	Hardness...........	Propeller hubs, small forgings
Chrome-Vanadium	S.A.E. No. 6150	0.45 to 0.55	0.50 to 0.80	0.040	0.040	....	0.80 to 1.10	Vanadium 0.15 to 0.25	200 000[b]	160 000	....	....	Gears and bolts
Chrome-Vanadium	S.A.E. No. 6195	0.90 to 1.05	0.20 to 0.45	0.030	0.030	....	0.80 to 1.10	Vanadium 0.15 to 0.25	....	....	....	Hardness...........	Pins, springs, special bearings

NOTE.—All bend tests made on material before quenching and tempering.

[a] For each 2000 lb. per sq. in. in excess of 55,000 lb. per sq. in. a reduction in elongation of one per cent to a minimum of 10 per cent will be allowed. These requirements must also be met after normalizing (heating to 1625° F. and cooling in air).

[b] Heat treated.

[c] Minimum core strength.

TABLE III.—SHEETS AND STRIPS; TUBES.

Material	Designation	Chemical Composition							Physical Properties								Uses
		Carbon, per cent	Manganese, per cent	Sulfur, per cent, max.	Phosphorus, per cent, max.	Nickel, per cent	Chromium, per cent	Other Elements, per cent	Tensile Strength, lb. per sq. in., min.	Yield Point, lb. per sq. in., min.	Elongation in 2 in., per cent, min.				Bend Test	Other Tests	
SHEETS AND STRIPS																	
Open-Hearth Iron	....	0.02	0.04	0.004	0.006	....	....	....	35 000	....	..	..	..	..	....	....	Deep forming & cupping, exhaust stacks
Extra Soft Low Carbon	S.A.E. No. 1010	0.05 to 0.15	0.30 to 0.60	0.050	0.045	....	....	....	38 000[a]	20 000	35	..	..	..	180 deg., flat	....	
Soft Low Carbon	S.A.E. No. 1015	0.10 to 0.20	0.30 to 0.60	0.050	0.045	....	....	....	45 000	25 000	22	..	..	..	180 deg., once thickness	....	Wheel rims
Quarter Hard Mild Carbon	S.A.E. No. 1025	0.20 to 0.30	0.50 to 0.80	0.050	0.045	....	....	....	55 000	36 000	22	..	..	..	180 deg., once thickness	....	Fittings, miscellaneous parts
High Carbon	S.A.E. No. 1095	0.70 to 0.85	0.25 to 0.50	0.045	0.040	....	....	....	....	....	..	..	..	..	180 deg., once thickness[b]	....	Springs, washers, tail skids, clips
		0.90 to 1.05	0.25 to 0.50	0.045	0.040	....	....	....	....	....	..	..	..	..		....	
Chromium	....	0.30 to 0.35	0.65 to 0.80	0.045	0.040	....	0.90 to 1.10	....	....	....	..	..	..	..	....	....	....
Chromium-Molybdenum	S.A.E. No. 4130X	0.25 to 0.35	0.30 to 0.60	0.045	0.040	....	0.80 to 1.10	Molybdenum 0.15 to 0.25	70 000[g]	40 000	25[c]	25[d]	20[e]	15[f]	180 deg., once thickness[c]	....	Structures, fittings, miscellaneous parts
									90 000[h]	60 000	20[c]	15[d]	12[e]	10[f]	135 deg., once thickness[e]	....	Structures, fittings, miscellaneous parts
Chromium-Vanadium	S.A.E. No. 6130	0.25 to 0.35	0.50 to 0.80	0.045	0.040	....	0.80 to 1.10	Vanadium 0.15 (min.)	....	....	..	..	..	..	180 deg., once thickness	....	Structures, fittings, miscellaneous parts
Nickel-Chromium	....	0.10 to 0.25	0.20 to 0.60	0.040	0.040	7.0 to 10.0	17.0 to 20.0	Silicon 0.10 to 0.70	95 000	45 000	45[c]	45[d]	40[e]	40[f]	180 deg., once thickness	....	Exhaust manifolds, structures, fittings
TUBES																	
Mechanical	No. 1015	0.10 to 0.20	0.30 to 0.60	0.050	0.045	....	....	....	50 000	30 000	..				....	Crush[i]	Exhaust stacks, water connections
Mild Carbon	No. 1025	0.20 to 0.30	0.50 to 0.80	0.050	0.045	....	....	....	55 000 65 000	36 000 40 000	22 15				....	Crush	Structural parts, fittings
Chromium-Molybdenum	No. 4130X	0.25 to 0.35	0.40 to 0.60	0.045	0.040	....	0.80 to 1.10	Molybdenum 0.15 to 0.25	95 000	60 000	10				....	....	Structural parts, fittings
3½-per-cent Nickel	No. 2330	0.25 to 0.35	0.50 to 0.80	0.050	0.040	3.25 to 3.75	....	....	85 000	60 000	10				....	....	Unwelded parts, axles

[a] Strips 40,000 lb. per sq. in.

[b] Annealed strip only.

[c] Sheets $\frac{3}{16}$ in. and thicker.

[d] Sheets $\frac{1}{8}$ to $\frac{3}{16}$ in.

[e] Sheets $\frac{1}{16}$ to $\frac{1}{8}$ in.

[f] Sheets less than $\frac{1}{16}$ in.

[g] Cold rolled.

[h] Hot rolled and annealed.

[i] Specimen full section of tube with a length equal to one and one-half times the outside diameter. Crush endwise under gradually applied load until the outside is increased in one zone by 25 per cent or until one complete fold is formed or the specimen is reduced to two-thirds its original length. The specimen shall stand this test without cracking.

ments given in Table II. This will insure that, after welding, the section affected by the heat still conforms to the minimum tensile strength requirements for the cold-finished bar. A carbon content of from 0.20 to 0.30 per cent fulfills this requirement.

SHEETS AND STRIPS

The airplane designer has always made extensive use of rolled sheet for the more important and highly stressed members (see Table III). The fabrication of these members often requires severe bends in any direction. The metallurgist has met these requirements by producing a sheet which will have equal tensile and bending properties, no matter what the angle of the axis of the specimen to the edges of the sheet. In the case of the carbon-steel sheet, the composition has been fixed so that the minimum tensile strength after welding (that is, in the area annealed by welding) shall be not less than 50,000 lb. per sq. in. and for the chromium-molybdenum sheet 80,000 lb. per sq. in.

The carbon-steel strip is made from hot-rolled strip which is severely worked by cold rolling, annealed to obtain an equiaxed grain and finally given a light draft for surface finish. The alloy sheet may be soft-annealed and finished by cold rolling or simply hot rolled and annealed or normalized for high tensile properties.

Strip steels of high carbon content are used in both the annealed and tempered condition, principally for springs.

TUBES

The seamless cold-drawn steel tube has afforded a means of obtaining economically, by means of simple welded joints, a structure which is rigid, resilient and of comparatively low weight (see Table III). The tubing can be drawn to a wall thickness of 0.020 in. or even less, but ordinarily 0.028 in. is the minimum for control surfaces and 0.035 in. for fuselage construction on account of the liability of injury in handling. The minimum wall thickness depends upon the diameter.

Mild carbon steel is used extensively for the smaller two or three-place airplanes. Chromium-molybdenum steel is used for transport airplanes and for military aircraft requiring a high load factor on account of violent maneuvering. The alloy-steel tube has excellent possibilities for heat-treated structures and is used for large welded assemblies heat-treated as a single unit. Tensile strength, of from 180,000 to 200,000 lb. per sq. in. have been used for axless tail skids and landing gear struts and 150,000 lb. per sq. in. for members of the fuselage and wing structure.

WIRE

Wire products have a rather extensive application as steel wire tension members and possess a strength-weight ratio superior to any other structural material (see Table IV). Wire is used in the form of single wires or stranded cable. Annealed, bright drawn, 3.50-per-cent nickel steel wire is used extensively for bolts, pins, clevises and a large variety of screw machine parts. The uniformity of the wire is tested by coarse-etching a specimen representing each end and middle of the coil of wire. The specimens used for coarse etching are blanks picked at random from the material as it passes through the cold-heading machines. These parts are generally heat treated to a tensile strength of 125,000 lb. per sq. in.

TABLE IV.—SIZES AND BREAKING LOADS OF AIRCRAFT CABLE.

Outside Diameter, in.	Breaking Load, lb. per sq. in.		
	Non-Flexible	Flexible	Extra-Flexible
0.062	500	480	....
0.078	780	550	....
0.094	1 100	920	....
0.109	1 600	....	....
0.125	2 100	1 350	2 000
0.156	3 200	2 600	2 800
0.187	4 600	3 200	4 200
0.218	6 100	4 600	5 600
0.250	8 000	5 800	7 000
0.312	12 500	9 200	9 800
0.375	17 500	....	12 500
0.438	23 500	....	14 400
0.500	28 500	....	....

The hard-drawn tinned wire which was used for tension members has been largely replaced by a cold-reverse-rolled tie rod of elliptical, round or square cross-section. This tie rod is manufactured from a cold-drawn circular wire containing from 0.40 to 0.55 per cent of carbon with a minimum tensile strength of 125,000 lb. per sq. in. The reverse rolling raises this to 150,000 lb. per sq. in. in the reduced section. Similar wires of corrosion-resistant chromium-nickel steel were raised to 200,000 lb. per sq. in. in the reduced section.

Cable may be classified as 19-strand non-flexible for tension members, 7 by 19 extra flexible for control lines, and 7 by 7 flexible for releasing mechanisms and lines requiring an intermediate flexibility. Chemical analyses and physical properties of the wire used in aircraft cables is similar to that used in other forms of high-grade wire rope. The sizes and breaking loads are shown in Table IV.

[For Discussion on Structural Metals, see page 171.—ED.]

STRUCTURAL AND ENGINEERING LIGHT ALLOYS FOR AIRCRAFT

BY R. L. TEMPLIN,[1] F. V. HARTMAN,[2] AND E. C. HARTMANN[3]

SYNOPSIS

This paper deals with the wrought and cast alloys of aluminum and magnesium which are best suited to aircraft work. Their advantages in the general field of aircraft construction are briefly discussed. The designation of the various alloys available is indicated and the forms in which the alloys are produced commercially are given. Tables of data are given on nominal composition, heat treatment, and mechanical properties.

The field of light metals for aircraft is limited at present to alloys whose chief constituent is either aluminum or magnesium, the former being the more commonly used at the present time. It is the purpose of this paper to discuss the use of these alloys in aircraft construction and to present data on their properties that will be of value in aircraft design.

The light alloy industry and the aircraft industry are mutually indebted. Each has contributed considerably toward the development of the other. On the one hand, the aircraft industry gave the initial impetus to the development of many of the light alloys and has stimulated their production to the extent that today they are available for all manner of structural uses. On the other hand, the light alloys industry has brought to the aircraft industry one of its most valuable materials, strong, reliable, durable, light, and well adapted to the manufacturing processes used. These light alloys have made possible the all-metal plane, the light-weight engine, the light-metal propeller, and the dirigible airship.

The present tendency of aircraft manufacture is toward all-metal constructions. The wooden plane with its fabric covers is too unreliable, flammable, short-lived, and difficult to repair; and it does not lend itself to modern factory methods of construction.

Metal construction is limited to the light alloys and to high-strength steel alloys. Comparing these two it is found that for members in which tensile strength is of prime importance the weight advantage is on the side of the light alloys unless the steel used has a yield point of about 90,000 lb. per sq. in. For the parts and fittings in which strength is not of primary importance it is usually impossible for steel to compete on a weight basis without the use of extremely thin sections. Ease of manipulation and durability are other factors that make the light alloys attractive for aircraft work.

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The present tendency toward metal coverings both in heavier-than-air and lighter-than-air craft makes the light alloys indispensable to the aircraft industry. Up to the present time steel has been found too heavy to be used for wing covering material. This means that the all-metal aircraft must be at least partly made of light alloys. The fact that there is a distinct advantage in having structure and covering of the same material in order to have a uniform modulus of elasticity throughout the construction provides another reason for favoring the light metals.

TABLE I.—APPROXIMATE COMPOSITION OF ALUMINUM ALLOYS MOST FREQUENTLY USED IN AIRCRAFT.

Alloy	Approximate Percentage of Other Elements Added to Aluminum				
	Copper	Manganese	Magnesium	Silicon	Nickel
Wrought:					
3S	...	1.25	...	...	...
17S	4.0	0.5	0.5	...	...
A17S	2.5	...	0.3	...	...
B17S	3.5	...	0.3	...	...
25S	4.5	0.8	...	0.8	...
51S	...	...	0.6	1.0	...
Cast:					
12	8.0	...	...	...	...
43	...	...	...	5.0	...
109	12.0	...	...	...	...
122	10.0	...	0.25	...	...
142	4.0	...	1.5	...	2.0
195–4	4.0	...	...	...	...
195–16	4.0	...	...	...	...

TABLE II.—DATA ON HEAT-TREATED ALUMINUM ALLOYS.

Alloy	Heat-treating Temperature		Approximate Time of Heating	Quench	Aging Temperature		Time of Aging
	deg. Fahr.	deg. Cent.			deg. Fahr.	deg. Cent.	
Wrought:							
17S	940 to 960	500 to 515	15 to 60 minutes	Cold water	Room	Room	4 days
A17S	940 to 960	500 to 515	15 to 60 minutes	Cold water	Room	Room	4 days
B17S	940 to 960	500 to 515	15 to 60 minutes	Cold water	Room	Room	4 days
25S	960 to 980	515 to 530	15 to 60 minutes	Cold water	285 to 295	140 to 145	8 to 15 hours
51S	960 to 980	515 to 530	15 to 60 minutes	Cold water	310 to 320	155 to 160	18 hours
Cast:							
195–4	940 to 960	500 to 515	12 hours	Hot water	....	....	....
195–16	940 to 960	500 to 515	12 hours	Hot water	310	155	3 to 5 hours

There are many light alloys available commercially, each having its own characteristics. In the following paragraphs those best suited

TABLE III.—MECHANICAL PROPERTIES OF WROUGHT ALUMINUM AND ALUMINUM ALLOYS.[a]

Alloy	Tension[b]			Shearing Strength,[d] lb. per sq. in.	Endurance Limit,[e] lb. per sq. in.
	Yield Point,[c] lb. per sq. in.	Ultimate Strength, lb. per sq. in.	Elongation in 2 in., per cent		
2SO	4 000	13 000	40	9 600	5 000
2S½H	14 000	17 000	20	11 000	7 000
2SH	21 000	24 000	10	13 000	8 500
3SO	5 000	16 000	40	11 000	6 000
3S½H	17 500	21 000	20	14 000	9 500
3SH	25 500	29 000	10	16 000	10 500
17SO	10 000	26 000	20	18 000	11 000
17ST	35 000	58 000	20	35 000	15 000
A17SO	8 000	22 000	22	15 000	......
A17ST	22 000	40 000	22	25 000	13 500
B17SO	8 000	22 000	22	15 000	......
B17ST	25 000	48 000	20	29 000	15 000
25SO	10 000	26 000	20	18 000	8 000
25SW	25 000	48 000	18	30 000	14 500
25ST	35 000	58 000	20	35 000	15 000
51SO	5 500	16 000	30	11 000	6 000
51SW	20 000	35 000	24	23 500	10 500
51ST	35 000	48 000	14	30 000	10 500

[a] Young's modulus of elasticity is approximately 10,000,000 lb. per sq. in.

[b] Standard tension-test specimens ½ in. in diameter.

[c] Yield point is the stress at which the stress-strain curve shows a departure of 0.2 per cent from the initial modulus line produced. Yield point in compression is practically equivalent to yield point in tension.

[d] Single shear strength values obtained from double shear tests.

[e] R. R. Moore type of rotating beam machine; endurance limit based on 500,000,000 cycles.

TABLE IV.—COMPARISON OF MECHANICAL PROPERTIES OF SOME ALUMINUM CASTING ALLOYS.[a]

Alloy	Tension[b]					Compression[c]		Shearing Strength,[e] lb. per sq. in.	Endurance Limit,[f] lb. per sq. in.
	Typical Values			Minimum Specification Values					
	Yield Point,[d] lb. per sq. in.	Ultimate Strength, lb. per sq. in.	Elongation in 2 in., per cent	Ultimate Strength, lb. per sq. in.	Elongation in 2 in., per cent	Yield Point,[d] lb. per sq. in.	Ultimate Strength, lb. per sq. in.		
No. 12	14 000	22 000	2.0	19 000	1.5	16 000	38 000	20 000	7 500
No. 43	9 000	19 000	4.0	17 000	3.0	9 000	25 000	15 000	6 500
No. 109	18 000	24 000	1.5	21 000	1.0	23 500	45 000	20 000	10 000
No. 112	14 000	22 000	2.0	19 000	1.0	24 000	44 000	20 000	8 500
No. 122	21 000	26 000	0.5	23 000	0.0	33 500	54 000	25 500	9 500
No. 142	24 000	28 000	1.0	23 000	0.5	34 000	52 000	24 000	8 000
No. 195–4[g]	16 000	31 000	8.0	28 000	6.0	27 000	43 000	27 000	6 000
No. 195–16[g]	22 000	36 000	4.0	30 000	3.0	28 000	43 000	29 000	6 000

[a] Young's modulus of elasticity is approximately 10,000,000 lb. per sq. in. for the above alloys.

[b] Standard sand-cast tension-test specimens ½-in. in diameter.

[c] Results of tests on specimens having an l/r of 20; all specimens failed by lateral bending.

[d] Yield point is the stress at which the stress-strain curve shows a departure of 0.2 per cent from the initial modulus line produced.

[e] Single-shear strength values obtained from double-shear tests.

[f] R. R. Moore type of rotating beam machine; endurance limit based on 500,000,000 cycles.

[g] Heat-treated alloys.

to aircraft work will be discussed in some detail to acquaint the reader with their properties and uses. In Table I are given the approximate chemical compositions of these alloys. The mechanical properties of the various wrought aluminum alloys are given in Table III, and similar data for the cast aluminum alloys are given in Table IV.

ALUMINUM ALLOYS

Wrought Alloys:

Commercially pure aluminum in its wrought form is called 2S by the principal manufacturer. Its strength and other mechanical properties depend upon the cold working or strain hardening which it receives in fabrication. For this reason it is necessary to designate the temper of the metal. In the annealed condition it is called 2SO. When it has received sufficient cold working to have properties in the maximum range it is said to be in the hard temper and is designated 2SH. The intermediate tempers are called quarter hard, half hard, and three-quarters hard; and 2S in these tempers is designated 2S¼H, 2S½H, and 2S¾H. Alloy 2S finds use in the aircraft field for fuel and oil tanks and lines, cowling, and other parts that are not highly stressed and which require severe forming operations.

The alloy called 3S is similar to 2S and is produced in the same tempers: namely, 3SO, 3S¼H, 3S½H, 3S¾H, and 3SH. In corresponding tempers, it is somewhat stronger than 2S, however, as indicated in Table III. It is used for the same purposes as 2S.

The wrought alloys shown in Table II are part of a group known as the strong alloys which depend upon heat-treatment for their high mechanical properties. The heat-treatment consists of heating the metal to a given temperature, quenching in cold water, and aging. Table II gives some data on the heat-treatment of the various alloys discussed in this paper.

The most important of the heat-treated wrought alloys in aircraft work is alloy 17S, often called duralumin. In the annealed condition it is called alloy 17SO. When heat-treated and aged as indicated in Table II it is called alloy 17ST. Alloy 17ST can be formed cold when the operation is not unusually severe and this procedure is generally followed for ordinary work on aircraft. When greater workability is required alloy 17SO is used and the formed piece is subsequently heat-treated to gain the maximum properties. Another procedure that is used with alloy 17S is to form it within one or two hours after it has been heat-treated, before it has had time to age appreciably. In this condition it is quite ductile. No further heat-treatment is needed in this case since the metal naturally ages to its full "T" condition in about four days.

Alloy 17ST is available in the form of flat sheet, plate, strip, corrugated sheet, tubing, shapes, rivets, bars, wire, forgings, fittings, and screw machine products.

Alclad 17ST is a very useful and interesting material for aircraft construction. It consists of 17ST sheet covered on each side with a thin surface layer of high purity aluminum, alloyed and integral with the core. These surface coatings protect the 17ST from corrosion not only on the unbroken surfaces but also, because of the electrolytic action, at the edges and other places where small areas are exposed.

Alclad alloy 17ST has the interesting property of being self-damping as regards vibration. The soft pure metal on the surface is stressed beyond its yield point by small deflections and this tends to retard the back swing, thereby providing a marked damping effect. The advantages of this in aircraft work where thin sections are used become readily apparent.

Alloys A17S and B17S will withstand more severe fabrication operations than alloy 17S. They are not as strong as 17S, however, and are not as widely used.

Alloy 25S is very similar to alloy 17S in some of its characteristics. It does not age at ordinary temperatures, however, and hence must be aged artificially at the temperature indicated in Table II to give its maximum properties. When heat-treated but not aged it is called alloy 25SW and it can be kept in this condition indefinitely at ordinary temperatures. In this respect it differs from alloy 17S which has no stable "W" condition. When heat-treated and aged, alloy 25S is called alloy 25ST, in accordance with the same nomenclature used with alloy 17S. Alloy 25S is used in aircraft chiefly in the form of forgings.

Alloy 51S, like alloy 25S, can be produced both in the "W" and "T" conditions. Alloy 51SW is very ductile and is therefore well adapted to cold-forming operations. After a piece has been formed from alloy 51SW it is usually aged to gain the higher mechanical properties of the "T" condition.

The strong alloys described above, when in the heat-treated condition, may be annealed by heating to 800° F., holding them at this temperature for at least one hour, and then cooling very slowly to below 500° F. When annealing these alloys before they have been heat-treated a different procedure is followed. The metal is heated rapidly to 650° F. and removed immediately from the furnace for cooling in air.

Casting Alloys:

The casting alloys most frequently used in aircraft are indicated in Table IV. The most important of these is probably alloy

No. 12, which is used whenever a general utility alloy is adequate. When castings must be leak-proof, alloy No. 12 is not suitable, and alloy No. 109 or No. 43 is substituted. Alloy No. 43 being lighter and better suited to withstand shocks, is often favored over alloy No. 109 for aircraft. Alloy No. 142 is sometimes used when high temperatures are to be encountered, as in certain motor parts. For pistons alloy No. 122 is used because it has the additional characteristic of offering greater resistance to wear.

Where castings must have high mechanical properties some heat-treated casting, such as alloy No. 195–4 or No. 195–16, is used. These two differ in that the latter is artificially aged after heat treatment. This process raises the yield point of alloy No. 195–16 to about 40 per cent greater than that of alloy No. 195–4 and also increases the strength somewhat. The ductility of the metal is decreased, however. Alloy No. 195–4 ages very slowly at ordinary temperatures and after three to six months attains properties practically as high as those of No. 195–16.

The casting alloys are usually sand cast, relatively little use being made of permanent-mold or die castings in aircraft work at present. The properties of permanent-mold castings are higher than those of sand castings for the same alloy. Aluminum castings machine easily and have a pleasing appearance. In general they can be cast with thinner minimum sections than can other commonly used metals.

MAGNESIUM ALLOYS

Considerable use is being made of magnesium castings for aircraft engine parts. The most common alloy used is designated alloy No. AM 7.4, containing approximately 7 per cent aluminum, 0.4 per cent manganese, and 92.6 per cent magnesium. The alloy may be used in the as-cast condition but is more frequently used in the heat-treated condition. Its physical properties are as follows:

CONDITION	AVERAGE TENSILE STRENGTH, LB. PER SQ. IN.	AVERAGE ELONGATION IN 2 IN., PER CENT	ENDURANCE LIMIT (ROTATING BEAM), LB. PER SQ. IN.	BRINELL HARDNESS NUMBER
As cast.............	24 000	6	8 500	45
Heat treated........	33 000	8	10 000	50

NOTE.—The results given above are obtained from a standard test bar $\frac{1}{2}$ in. in diameter, cast in sand molds without chill or artificial means of cooling and tested without machining off the surface. Evidence indicates, however, that approximately the same results are obtained on machined specimens.

This alloy weighs about 113 lb. per cu. ft. Castings made of it are therefore approximately one-third lighter than aluminum-alloy castings and thus result in a decrease in weight of one pound in every three as compared with aluminum.

This alloy is used for aircraft engine parts, such as pumps, gear covers, and even supercharger housings. While the alloy has not yet been used for major structural parts, a comparison of its properties with those of aluminum castings indicates alluring possibilities.

[For Discussion on Structural Metals, see page 171.—ED.]

THE HIGHLY-ALLOYED STEELS IN AIRCRAFT CONSTRUCTION

By Jerome Strauss[1]

Synopsis

This paper refers in a general way to the use of the corrosion-resisting steels in the manufacturing industries and in particular to the need for extreme precautions in order to secure the highest possible quality in these steels when employed for parts of aircraft. The properties of the various plain chromium and chromium-nickel steels are given, including not only the mechanical properties required for the determination of design stresses, but also the fabricating properties, and the precautions to be observed in the use of the different steels in order that the designer may better adapt these materials to specific needs.

During the few years of their commercial life, the corrosion-resisting steels have found entry to practically every phase of industrial activity. Marine construction and the chemical and oil industries have been the major users, but even though in a small way in so far as tonnage is concerned, their value in solving the problem of permanence in other fields has been no less marked. Aircraft construction is no exception. It is, of course, true that there has been no real standardization of any of these steels for specific aircraft parts and that the use of many of them in the structural parts and engine parts of flying craft is in the experimental stage. But this is more or less true of all their applications; compositions are changing, the steel making and shaping methods are changing, heat-treatment procedures are changing, fabricating practices are changing; the entire metallurgical and mechanical development is in a state of flux, and the user is endeavoring through study in a practical way to determine the best solution of his problems. Hence it seems best to present at this time only a brief statement of the properties of those compositions that possess promise and an indication of the purposes to which they may be suited.

Of primary importance to the aircraft designer is the weight of the elements of his structure. As a result he desires, and frequently does employ, materials under conditions involving a low safety factor and with it must demand of them as near perfection as can be obtained, for the hazard is great and loss through material failures must be carefully guarded against. The significance of steel quality and of adequate inspection in order that reliability may be assured, are therefore apparent. Too much emphasis cannot be placed upon these two features. There is required the closest possible approach to perfection in avoiding or eliminating surface and internal discontinuities and in maintaining uniformity of grain size and grain characteristics to permit uniform response to heat treatment. There is also the necessity for fabricating operations that are closely controlled within limits that are not detrimental to the particular composition involved, carefully supervised heat treatment and finishing operations, and close inspection at all stages of production by those competent to accept or discard. Only by such thorough practices can reliability be assured and the hazard diminished. This, of course, assumes that design features have been carefully studied and the parts are in this respect well adapted to their intended service and likewise that steel composition has been suitably selected.

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It is, of course, natural that in engine design, the experience of the automobile industry should have been very largely drawn upon. And it is, therefore, no surprise that, for valve construction one of the lower-chromium steels with high silicon has found much favor. This steel has the nominal composition: carbon, 0.40 per cent, chromium, 8.5 per cent, and silicon, 3.5 per cent and responds readily to forging and to heat treatment. Through quenching and tempering, a range of properties may be secured about as follows:

Proportional limit, lb. per sq. in.	75 000 to 125 000
Tensile strength, lb. per sq. in.	125 000 to 210 000
Elongation in 2 in., per cent	25 to 2
Reduction of area, per cent	55 to 4

The treatment of valves usually consists of quenching in oil from 1900° F. followed by tempering at 1400° F. and subsequently requenching the tip from the same temperature and tempering at 400° F. Valves in this condition serve very well and scale only slightly even when operating temperatures approach 1400 to 1500° F., but they are not especially strong at this temperature and flow and gall slightly on the stem.

The higher-chromium steels also offer possibilities for the designer of aircraft. So-called "stainless iron" having a nominal composition of carbon, 0.10 per cent, chromium, 12.5 per cent may have its properties appreciably varied by heat treatment, quenching in oil from about 1750° F. followed by tempering producing the following range of tension and impact test values:

Proportional limit, lb. per sq. in.	30 000 to 125 000
Tensile strength, lb. per sq. in.	80 000 to 190 000
Elongation in 2 in., per cent	35 to 13
Reduction of area, per cent	75 to 40
Modulus of elasticity, lb. per sq. in.	30 000 000
Izod impact value, ft-lb.	115 to 30

This steel in moist atmosphere will acquire a film of corrosion product in time, but rusting then practically ceases (assuming, of course, metal of high quality). It will remain scale-free in air up to about 1200° F. and still possess moderate strength at this temperature. Forging is readily carried on, using practically the same practice as for carbon and low-alloy steels; air cooling from the forging heat, however, results in hardening up to the maximum shown in the above range of tensile properties. Machining may be carried on very satisfactorily at speeds slightly less than those employed for simple steels of equal tensile strength. Corrosion resistance is influenced only slightly by heat treatment, but is somewhat higher after quenching and tempering than in the annealed condition. Maintenance of the alloy at elevated temperatures does not result in grain growth and consequent brittleness unless the chromium content is somewhat above 13 per cent and high temperatures are maintained for rather long periods. The metal may be brazed or soldered and may also be welded but the welds are hard and lacking in toughness unless the welded assembly is subjected to suitable heat treatment. Hardening may also be effected by cold working, producing in small wires, for instance, tensile strengths up to 200,000 to 250,000 lb. per sq. in., and in this condition the alloy may be used for springs and like applications; the resistance to corrosion is not noticeably impaired by this uniform distortion These various properties suggest, naturally, a number of applications among which may be noted propeller hubs, exposed engine parts, springs, stream line wires, etc. The steel is available in many forms, including hot-rolled and cold-drawn bars, forgings, wire, strip, wire rope, sheets, seamless tubing, etc.

In the interest of producing a "stainless iron" that would lend itself to smoother and faster machining and thereby permit the manufacture of screw machine products of corrosion-resistant steel, a number of modifications of this composition have been developed. In these the carbon content is approximately the same, the chromium content about one per cent greater and uniformly distributed throughout the metal in very fine dispersion is a suitable non-metallic body that breaks the continuity of chips removed by cutting tools in quite the same manner as in "screw stock," thus imparting "free-turning" properties. The composition is so chosen that corrosion resistance is approximately the same as for "stainless iron" but the temperature required for effective quenching is raised about 75° F. and the maximum strength obtainable by heat treatment is only about 135,000 lb. per sq. in. In other respects the properties are quite similar and the same commercial forms may be produced. Where rapid or automatic machining is desired or finer finish by machining, grinding or polishing is demanded, and the mechanical properties are ample, material of this class is indicated.

The higher-carbon medium-chromium steel known as "stainless steel" also has a few possible aircraft applications. Its composition is normally about carbon, 0.30 per cent, chromium, 13.5 per cent. It is capable of greater hardening than the lower-carbon steel and after oil quenching from about 1850° F. will show on tempering the following range of properties:

Tensile strength, lb. per sq. in	90 000 to 260 000
Proportional limit, lb. per sq. in	50 000 to 140 000
Elongation in 2 in., per cent	25 to 2
Reduction of area, per cent	60 to 3
Modulus of elasticity, lb. per sq. in	30 000 000
Izod impact value, ft-lb	65 to 5

It possesses a very much greater variation in resistance to corrosion with change in thermal treatment, being best in the hardest condition, but even in this state is somewhat inferior to "stainless iron." It is this hardest form in which it is likely to be of interest for aircraft use, chiefly for ball or roller bearings or other bearing surfaces. In forging, the alloy behaves quite like high-speed steel and in machining operations is quite comparable to the low-alloy steels of somewhat higher tensile strength.

Two other chromium steels of slightly different composition, but somewhat similar properties and applicable to the same class of service, may be noted:

Carbon 0.60 per cent, Chromium 16.5 per cent,
Carbon 1.10 per cent, Chromium 17.0 per cent, Silicon 1.0 per cent

Both compositions develop approximately the same degree of corrosion resistance as the "stainless steel" but both also may be heat treated to higher hardness values and greater compressive strength. These steels remain scale-free up to about 1400° F. and at this temperature still possess moderate strength.

Mention must be made of one other medium-chromium steel, much used for valve construction. Its composition is carbon 1.30

per cent, chromium 12 per cent, cobalt 3.5 per cent, molybdenum 0.75 per cent. The thermal treatment employed is frequently a heating to 1650° F. followed by relatively slow cooling to 1300° F. and then cooling in air. This steel at the maximum temperatures used in motor operation scales slightly from the attack of exhaust gases but possesses excellent strength and consequently does not show distortion or galling of the stem.

Other plain chromium corrosion-resisting steels of much merit are regularly manufactured for a variety of commercial uses but in aircraft production could have no more than limited and unimportant applications and need therefore not be considered.

The quaternary chromium steels containing nickel as a principal component are, however, of great industrial importance and value and offer many possibilities in the design of flying craft. There are a number of types in use but it appears necessary to give detailed consideration to only a few of these. The nominal compositions are:

Carbon 0.12 per cent, Chromium 18.0 per cent, Nickel 8.0 per cent
Carbon 0.06 per cent, Chromium 18.0 per cent, Nickel 8.0 per cent
Carbon 0.15 per cent, Chromium 18.0 per cent, Nickel 8.0 per cent, Silicon 1.0 per cent, Tungsten 4.0 per cent
Carbon 0.25 per cent, Chromium 18.0 per cent, Nickel 25.0 per cent, Silicon 2.5 per cent
Carbon 0.20 per cent, Chromium 26.0 per cent, Nickel 21.0 per cent, Silicon 2.5 per cent

All of these steels are austenitic, technically non-magnetic and do not harden by quenching but only by cold deformation.

The first of the group is the one most commonly used and of the greatest importance. It possesses extremely high resistance to corrosion and in moist atmosphere, if a well-made product suitably finished, may be expected to remain rust-free for an indefinite period. In its softest condition, secured by rapid cooling from 1950 to 2150° F. it shows the following approximate range of tensile properties depending upon the exact composition, heat treatment, form and cross-section:

Tensile Strength, lb. per sq. in.	80 000 to 100 000
Yield Point, lb. per sq. in.	30 000 to 55 000
Elongation, in 2 in., per cent	65 to 50
Reduction of Area, per cent	75 to 50
Modulus of Elasticity, lb. per sq. in.	27 500 000
Izod Impact Value, ft-lb	100 to 120

In this condition the proportional limit, carefully determined, may be found to be below 10,000 lb. per sq. in. In the hot-rolled condition the mechanical properties are notably higher, especially the proportional limit, and on cold working they increase still further. In fact, this alloy, more ductile than any carbon or low-alloy steel and capable of much greater deformation without rupture in forming and drawing, likewise hardens more rapidly with cold work than any of the simple steels. When deformed the tensile strength rises rapidly but the proportional limit and yield point are increased even more rapidly. In thin sheets, tensile strengths as high as 200,000 lb. per sq. in. may be obtained and in small wires up to 230,000 lb. per sq. in.; it is interesting to note that this "hard" sheet is still very ductile and may be successfully carried through some forming operations. Machining of this steel may be accomplished, but with some difficulty and only at speeds much below those used for the plain chromium corrosion-resisting steels. Unfortunately as the strength properties are increased by working, machining becomes rapidly more difficult, in particular such operations as milling and drilling. While corrosion resistance is ample in any state for aircraft uses, it reaches a maximum after the softening quench noted above. It is also worthy of note that it offers very great resistance to the combined effects of stress and corrosion. Furthermore it retains much of its ductility at low temperatures, in fact, down to the boiling point of liquid air and possibly lower.

This steel is readily forgeable by ordinary methods but is very rigid at forging temperatures and should not be worked, especially in intricate forms, much below 1700° F. While some alteration occurs on long exposure at moderately high temperatures, there is some question as to whether real "brittleness" develops; pending the accumulation of more data it is well nevertheless to avoid long exposure within the range of 900 to 1700° F. In use, parts of this steel will show no scale formation up to 1600° F. and at this temperature the alloy shows a strength which is a fair proportion of its strength at room temperatures. It may be soldered or brazed but as there is a possibility of intercrystalline penetration of the brazing metal with consequent danger in highly stressed joints or those subjected to moderately high temperatures, welding is to be preferred. The latter method of joining may be readily accomplished and will leave a finished article devoid of brittleness and in most cases possessing satisfactory chemical and mechanical properties in and adjacent to the weld, without further heat treatment. It is important to note that the coefficient of expansion of this steel is appreciably greater than that of the simple steels and also the plain high-chromium steels, exceeding that of the latter by almost 40 per cent. With the fabricating and mechanical properties just described many uses are to be anticipated and it has therefore been employed in pontoons, in fittings, in stream line wire and in fuselage tubing. While fabrication by steel producers has not by any means been devoid of difficulties, this steel has nevertheless been produced in quantity in many forms—hot-rolled and cold-drawn rods, seamless and welded tubing, sheets, plates, wire, rivets, strip, and many other forms.

The low-carbon variety of this same composition possesses most of the desirable qualities of the principal type just described. It does not, however, require the drastic quench for maximum corrosion resistance, is generally softer and more ductile and hardens slightly less readily as a result of working; it has, however, a modulus of elasticity of 1,000,000 or 2,000,000 lb. per sq. in. less than the higher-carbon type and for like processing lower elastic strength. There is also reason to anticipate a reduced tendency toward "brittleness" on long heating in the temperature range of 900 to 1700° F.

The other chromium-nickel types noted are all of the same general character and of particular value because of their resistance to oxidation and their high strength at temperatures well above a red heat. The first two of these three compositions remain practically scale-free at 1800° F., while the same is true of the last one at 2000° F.; they are still very serviceable at 200° F. above these temperatures. Such properties obviously fit them for service as valves, exhaust ports, and similar uses. Unfortunately they are very rigid in forging and extremely difficult to machine and these properties must be given due consideration when determining upon their use.

The foregoing brief treatment of the corrosion-resisting steels has not attempted the inclusion of all of the composition modifications that have been proposed and used. Only those of first importance have been described, but it is hoped that this cursory treatment will serve as a guide in the selection of suitable materials for specific uses and hence may prove of some value.

Acknowledgment.—Grateful acknowledgment is made of information furnished by J. A. Mathews, Vice-President and Metallurgist, Crucible Steel Co. of America, and B. H. De Long, Metallurgist, Carpenter Steel Co.

[For Discussion on Structural Metals, see page 171.—ED.]

STRENGTH AND CHARACTERISTICS OF WOOD USED IN AIRCRAFT CONSTRUCTION

By G. W. Trayer[1]

Synopsis

Wood has been the pioneering structural material in aircraft. Its exceptional advantages for small sizes and experimental types are unquestioned, and it continues to be one of the major materials of commercial aircraft development. The chief qualities that have won this position for wood are: A high ratio of strength to weight; cheapness; lightness, affording readily the size of member required to resist twisting and lateral buckling; suitablility for close designing; the facility with which it can be worked into various structural shapes and assembled; the facility of repair without specialized equipment; and adaptability to small-scale production. A lack of uniformity in the quality of wood is perhaps the most important factor militating against its future use in large-scale production. The existing detailed knowledge of the properties of wood and the causes of variation in them, determined at the Forest Products Laboratory, now makes it possible to select aircraft material with assurance, however, and thus places design on a reliable basis. With improvement in the methods of selecting and manufacturing the lumber and continued improvement in the fabrication methods, there is every reason to think that wood can be used for aircraft on a mass production basis.

Strength values of the woods most commonly used for aircraft design, for a 15-per-cent moisture condition of material and a 3-second duration of stress, are presented, together with a discussion of the various factors that affect these values.

Selection of Aircraft Wood

The chief merits of wood as a structural material for aircraft are high ratio of strength to weight, cheapness, adaptability to small-scale production, suitability for close designing, and the facility with which it can be worked into various structural shapes and assembled. Lack of uniformity in quality, however, militates against the smooth flow of processes that is essential to quantity production. The chief problem in its use, then, is to take proper cognizance of the factors that affect strength and variability. The principal causes for the variations in strength have been determined at the Forest Products Laboratory and consequently these variations can be largely eliminated by proper specifications and inspection. In the following discussion, the principal causes are explained and the precautions necessary in selecting wood for satisfactory quantity production of aircraft are presented.

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Strength as Related to Specific Gravity:

In general, a piece of wood of high specific gravity is stronger than a light piece. Fairly definite mathematical relations between specific gravity and the various strength properties have been determined experimentally.[1] Some of the strength properties of wood vary as the first power of its specific gravity, others, with higher powers. The minimum strength values of a particular lot of lumber can be greatly raised by eliminating a relatively small portion of the lighter material. Accordingly, minimum specific gravity values are included in specifications for aircraft parts. The light-weight material can as a rule be detected by visual inspection, but to assist aircraft inspectors in studying the relation between appearance and specific gravity, actual determinations are occasionally made.

Strength as Related to Moisture Content:

When a piece of green or saturated wood is dried, the free water from within the cell cavities first moves out to the surrounding atmosphere. The free water has no effect on volume or strength, but after it has been removed and the remaining moisture begins to come from the cell walls, the wood shrinks and normally increases rapidly in strength. The point at which the free water becomes exhausted is called the fiber-saturation point. Since there is an increase in strength as the cell walls become drier and drier, proper design values for airplane construction are partly dependent upon the moisture content that the structure will ultimately reach in service. After a careful survey of conditions, the Army and Navy Aeronautical Bureaus adopted a 15-per-cent moisture content as a standard and design stresses have accordingly been based on that condition.

Strength as Related to Locality of Growth:

It may be said that material of a given species, and of given specific gravity, grown in one locality will usually have the same strength as material of the same specific gravity grown somewhere else. There are a few cases in which the material from a certain region averages lower in strength than that from another but the weight also averages correspondingly lower. The Rocky Mountain type of Douglas fir, for example, averages considerably lower both in strength and in weight than the Coast type.

Strength as Related to Rate of Growth:

It is impossible to set up a general rule for variation in strength with rate of growth. Coniferous species, such as spruce, of very rapid growth are likely to fall below the average in strength. Hence the present limitation for aircraft spruce is that it shall have at least six annual growth rings per inch. Hardwoods of very rapid growth, on the other hand, are usually above the average in strength properties. An exception to this rule will be found in the swelled-butt material of swamp-grown ash and tupelo gum. Such material, while of rapid growth, is brash and inferior in weight and strength.

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[1] J. A. Newlin and T. R. C. Wilson, "The Relation of the Shrinkage and Strength Properties of Wood to Its Specific Gravity," *Bulletin No. 676*, U. S. Department of Agriculture.

Strength as Related to Position in the Tree:

As a general rule, wood of the highest specific gravity is the strongest regardless of its position in the tree. The exceptions to this rule are confined mostly to the lower ten or twelve feet of the tree. Slight variations with distance from the pith that are not entirely explained by differences in density have been observed, but they are not of sufficient importance to be considered.

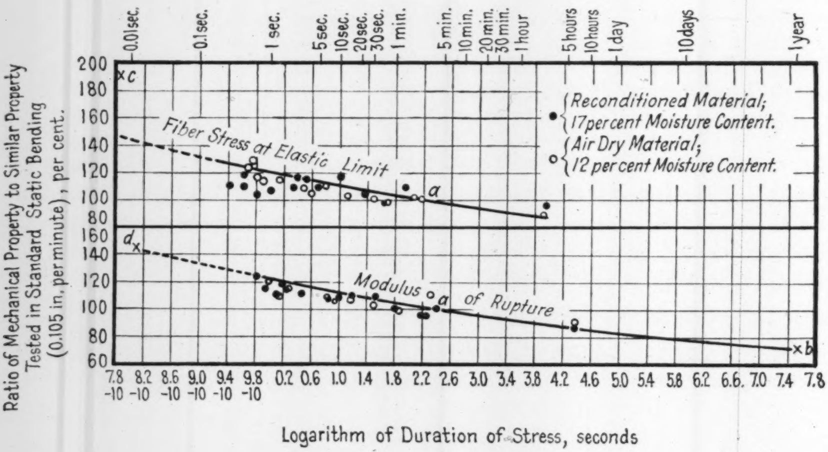

FIG. 1.—Relation Between Fiber Stress at Elastic Limit and Modulus of Rupture of Sitka Spruce and Duration of Stress.

Points marked *a* represent the strength in standard static bending.

The data for point *b* were taken from previous dead load tests. The duration of stress was 6 months to a year or more.

Data for point *c* were taken from *Bulletin No. 556*, U. S. Department of Agriculture.

Location of point *d* was estimated.

Duration of stress is the total time between application of load and elastic limit or maximum load.

Strength as Related to Duration of Stress:

The time that a wooden member is required to resist a given stress is a very important factor in the amount of stress causing failure; such a member will resist an extreme load of short duration The standard laboratory static test requires several minutes, while the maximum stress on a main structural part of an airplane in coming out of a dive or similar maneuver is maintained for only a few seconds. Accordingly, the allowable stresses as obtained from static tests are increased to take care of this condition. For the 3-second duration of maximum stress assumed as standard the increase adopted is 17 per cent. Figure 1 shows the relation between fiber stress at elastic limit in bending and the duration of stress to the elastic limit, and the relation between modulus of rupture and the duration of stress to maximum load. As evidenced by the outer ends of both curves dropping below the 100-per-cent level, a continuously applied load only slightly greater than that required to develop the fiber stress at elastic limit in the ordinary static test will ultimately cause failure. Loads of short duration may safely be above this amount.

DEFECTS AFFECTING STRENGTH

In aircraft construction, the maintenance of structural strength with a minimum of weight demands that the tolerance of defects, in specifications, be far from liberal.

Deviation in Grain.—Diagonal or cross grain is produced when the saw cut is not parallel to the bark. It can usually be avoided, by exercising care in sawing, if the logs are free from crook. Spiral grain results from the spiral arrangement of the fibers in the tree and cannot be entirely compensated for in the sawing operation. Tests have shown that the weakening effect of spiral or diagonal grain is accompanied by an increased variability of the properties. The weakening effect is noticeable at a slope of about 1 in 20 and increases rapidly as the slope becomes more pronounced. These facts result from the great difference in the properties of wood in the various directions relative to the grain. The tensile strength, for example, may be 20 or more times as high parallel to the grain as perpendicular, and the crushing strength from 2½ to 8½ times as high. In general, a slope of grain greater than 1 in 20 should not be permitted in a main structural member. In other parts, whose failure in service would not affect the structure proper, a slope of 1 in 15 is allowable.

Knots, pitch pockets, wavy grain, curly grain, interlocked grain, and indented rings are objectionable from a strength standpoint chiefly because of the discontinuity and distortion of the grain that they cause. Knots ¼ in. in diameter may be permitted near the neutral axis and along the middle of the top and bottom surfaces of main structural members, provided they are not closer together than 10 in. and do not cause a divergence of grain at the edges of the member beyond 1 in 20. Where less severe strength requirements permit a slope of 1 in 15, knots up to $\frac{1}{2}$ in. in diameter may be used, provided they are not closer together than 20 in. and do not cause a divergence of grain at the edges of the member greater than the allowable figure. With this tolerance the loss in strength is negligible.

Pitch pockets may be permitted on the same basis as knots. Wavy, curly, and interlocked grain are subject to the same limitations as spiral or diagonal grain. The indentations of the annual rings as occasionally seen on an end section of some coniferous species, such as spruce, result in a slight irregularity of the grain. On tangential surfaces these indentations appear as scars. Their effect is less than that of the permissible pin knot and in members of appreciable size they may be permitted.

Mineral Streaks.—Mineral streaks are dark brown or blackish streaks, often with a greenish tinge, that contain more or less mineral matter, often in sufficient quantities to dull sharp-edged tools. They are usually associated with an injury of some kind and are frequently accompanied by decay. All boards showing any evidence of decay are rejected in accordance with aircraft specifications.

Compression Wood.—In coniferous species medium to wide annual growth layers of abnormal wood often form between normal growth layers and, as a rule, they shade out into the normal growth. This material, which is now readily recognized by inspectors and mechanics, has a large end shrinkage and when contained in a board causes unusual warping. It has low strength properties for its weight. Pieces containing this so-called compression wood are not permitted in aircraft construction.

Compression Failures.—Excessive bending of standing trees from wind or snow, felling logs across irregularities in the ground, or the rough handling of logs and lumber may produce excessive compressive stresses along the grain that cause minute compression failures. All material containing such failures should be eliminated from airplane parts in which strength is important.

Decay.—The early stages of decay are evidenced by discolorations of the wood and any discoloration, therefore, must be regarded with suspicion and the pieces containing it carefully examined. Some discolorations are harmless molds or stains having no effect upon the strength, but, as a general rule, when conditions are right for the development of harmless stains they also favor the development of serious decay. In early stages of decay the shock-resisting ability of wood is the most affected while in the late stages all properties drop rapidly. When acceptance is based entirely upon specific gravity and appearance, all boards containing any evidence of decay should be rejected.

Seasoning Defects.—Unless the drying of wood is done with exceptional care, stresses that are manifested by checking, honeycombing, case hardening, collapse, warping, and so forth, are likely to be introduced. These stresses are due to the unequal distribution of moisture during the drying process and the resulting unequal shrinkage that takes place, and also to the difference in radial and tangential shrinkage. In air drying, large differences in the distribution of moisture are avoided and the internal stresses are accordingly not very great; this is particularly true in the early part of the drying, which is quite critical. Careful kiln drying will produce results at least equal and perhaps superior to those obtained through long periods of air seasoning. Honeycombing, collapse, and checking are causes for certain rejection, but the acceptance or rejection of warped or case-hardened stock depends upon the degree to which the stock is affected.

Manufacturing Defects.—The finish of a wooden airplane member need only be sufficient to produce a good surface for varnishing. Pieces with slightly lifted grain or surfaces slightly splintered in machining should not be rejected. In routed beams, for example, splinters where the shaper knife finishes out against the grain need not be a cause for rejection unless the splintering enters the flanges.

AVERAGE STRENGTH VALUES MODIFIED FOR AIRCRAFT DESIGN

Wood is slightly more variable than most other materials used in the construction of highly stressed aircraft parts. Furthermore, since most of the strength values of wood increase more rapidly than its density, the variability curves for most properties are skewed and more values fall below the average than above. Accordingly, in arriving at design values, probability curves for the various properties were constructed. As a result, the average fiber stress at elastic limit and the modulus of rupture in bending, and the average fiber stress at elastic limit and the maximum crushing strength in compression parallel to the grain were reduced by 6 per cent. The modulus of elasticity is somewhat more variable than these other properties and it was therefore reduced by 8 per cent. For all other properties entering into aircraft design average test values were used. With these reductions and a minimum specific gravity requirement, the design stresses for wood are put on a parity with metals as regards reliabilty.

DESIGN STRESSES FOR AIRCRAFT WOOD

In Table I are given the design stresses for woods commonly used in aircraft construction. The table, which was prepared by the Forest Products Laboratory, has been adopted by the Army Air Service, the Bureau of Aeronautics, Navy Department, and the Depart-

TABLE I.—STRENGTH VALUES FOR AIRCRAFT WOODS AT 15-PER-CENT MOISTURE CONTENT.

Species of Wood; Common and Botanical Names	Specific Gravity Based on Volume and Weight When Oven Dry		Weight at 15 per cent Moisture Content, lb. per cu. ft.	Shrinkage[g]		Static Bending				Compression Parallel to Grain		Compression Perpendicular to Grain, lb. per sq. in.[i]	Shearing Strength Parallel to Grain, lb. per sq. in.[j]	Hardness, lb.[k]
	Average	Minimum Permitted		Radial, per cent	Tangential, per cent	Fiber Stress at Elastic Limit, lb. per sq. in.	Modulus of Rupture, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Work to Maximum Load, in-lb. per cu in.	Fiber Stress at Elastic Limit, lb. per sq. in.[h]	Maximum Crushing Strength, lb. per sq. in.			
HARDWOODS (BROAD-LEAVED SPECIES)														
Ash, black (*Fraxinus nigra*)	0.53	0.48	35	5.0	7.8	6 400	11 900	1 340 000	14.3	4050	5400	1260	1050	760
Ash, commercial white (*Fraxinus* spp.)[a]	0.62	0.56	41	4.3	6.9	8 900	14 800	1 460 000	14.2	5250	7000	2250	1380	1180
Basswood (*Tilia glabra*)	0.40	0.36	26	6.6	9.3	5 600	8 600	1 250 000	6.6	3370	4500	620	720	370
Beech (*Fagus grandifolia*)	0.66	0.60	44	4.8	10.6	8 200	14 200	1 440 000	13.5	4880	6500	1670	1300	1060
Birch (*Betula* spp.)[b]	0.68	0.58	44	7.0	8.5	9 500	15 500	1 780 000	18.2	5480	7300	1590	1300	1100
Cherry, black (*Prunus serotina*)	0.53	0.48	36	3.7	7.1	8 500	12 500	1 330 000	11.7	5100	6800	1170	1180	900
Cottonwood (*Populus deltoides*)	0.43	0.39	29	3.9	9.2	5 600	8 600	1 190 000	7.4	3520	4700	650	660	410
Elm, rock (*Ulmus racemosa*)	0.66	0.60	45	4.8	8.1	7 900	15 000	1 340 000	19.3	5180	6900	2090	1360	1230
Gum, red (*Liquidambar styraciflua*)	0.53	0.48	34	5.2	9.9	7 500	11 600	1 290 000	10.9	4050	5400	1190	1100	650
Hickory (true hickories) (*Hicoria* spp.)[c]	0.79	0.71	51	...	...	10 600	19 300	1 860 000	27.5	6520	8700	3100	1440	...
Mahogany, African (*Khaya* spp.)	0.47	0.42	32	4.8	5.5	7 900	10 800	1 280 000	8.0	4280	5700	1400	980	720
Mahogany, true (*Swietenia* spp.)[d]	0.51	0.46	34	3.4	4.7	8 800	11 600	1 260 000	7.3	4880	6500	1760	860	790
Maple, sugar (*Acer saccharum*)	0.67	0.60	44	4.8	9.2	9 500	15 000	1 600 000	13.7	5620	7500	2170	1520	1270
Oak, commercial white and red (*Quercus* spp.)[e]	0.69	0.62	45	4.6	9.0	7 800	13 800	1 490 000	13.6	4950	6600	1870	1300	1240
Poplar, yellow (*Liriodendron tulipifera*)	0.43	0.38	28	4.0	7.1	6 000	9 100	1 300 000	6.5	3750	5000	810	800	420
Walnut, black (*Juglans nigra*)	0.56	0.52	39	5.2	7.1	10 200	15 100	1 490 000	11.4	5700	7600	1730	1000	990
SOFTWOODS (CONIFERS)														
Cedar, incense (*Libocedrus decurrens*)	0.36	0.32	25	3.3	5.7	6 000	8 700	1 020 000	5.6	4320	5400	900	650	450
Cedar, Port Orford (*Chamæcyparis lawsoniana*)	0.44	0.40	30	4.6	6.9	7 400	11 000	1 520 000	8.7	4880	6100	1030	760	520
Cedar, western red (*Thuja plicata*)	0.34	0.31	23	2.5	5.1	5 100	7 800	1 030 000	5.8	4000	5000	800	630	320
Cedar, northern white (*Thuja occidentalis*)	0.32	0.29	22	2.1	4.9	4 700	6 600	700 000	4.9	3040	3800	560	610	300
Cyresss, southern (*Taxodium distichum*)	0.48	0.43	32	3.9	6.1	7 100	10 500	1 270 000	7.7	4960	6200	1230	720	480
Douglas fir (*Psuedotsuga taxifolia*)	0.51	0.45	34	5.0	7.8	8 000	11 500	1 700 000	8.1	5600	7000	1300	810	620
Pine, Norway (*Pinus resinosa*)	0.51	0.46	34	4.6	7.2	8 500	11 900	1 560 000	8.9	5280	6600	1080	870	520
Pine, sugar (*Pinus lambertiana*)	0.38	0.34	26	2.9	5.6	5 600	8 000	1 040 000	5.4	3680	4600	810	730	370
Pine, western white (*Pinus monticola*)	0.42	0.38	27	4.1	7.4	6 000	9 300	1 310 000	7.9	4240	5300	750	640	360
Pine northern white (*Pinus strobus*)	0.38	0.34	26	2.2	6.0	5 900	8 700	1 140 000	6.3	3840	4800	780	640	380
Spruce (*Picea* spp.)[f]	0.40	0.36	27	4.1	7.4	6 200	9 400	1 300 000	7.8	4000	5000	840	750	440

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[a] Includes white ash (*F. americana*), green ash (*F. pennsylvanica lanceolata*), and blue ash (*F. quadrangulata*).

[b] Includes sweet birch (*B. lenta*) and yellow birch (*B. lutea*).

[c] Includes bigleaf shagbark hickory (*H. laciniosa*), mockernut hickory (*H. alba*), pignut hickory (*H. glabra*), and shagbark hickory (*H. ovata*).

[d] Includes material from Central America and Cuba.

[e] Includes white oak (*Q. alba*), bur oak (*Q. macrocarpa*), swamp chestnut oak (*Q. prinus*), post oak (*Q. stellata*), red oak (*Q. borealis*), southern red oak (*Q. rubra*), laurel oak (*Q. laurifolia*), water oak (*Q. nigra*), swamp red oak (*Q. pagodæfolia*), willow oak (*Q. phellos*), and yellow oak (*Q. velutina*).

[f] Includes red spruce (*P. rubra*), white spruce (*P. glauca*), and Sitka spruce (*P. sitchensis*).

[g] From green to oven dry condition based on dimensions when green.

[h] Values, to nearest 10 lb., are 0.75 max. crushing strength for hardwoods, 0.80 for conifers.

[i] Average fiber stress at elastic limit test values corrected for 3-second duration and then increased 33⅓ per cent.

[j] Average test values multiplied by 0.75.

[k] Side load required to embed 0.444-in. ball to one-half its diameter.

ment of Commerce. Minimum and average specific gravities are included in the table as well as weight per cubic foot at 15-per-cent moisture content. It is assumed that in using the design stresses listed the limits mentioned under "Defects Affecting Strength" will be strictly adhered to. The values listed have been adjusted for a 3-second duration of load and for the variations from the average noted in the preceding paragraph. The modulus of elasticity is obtained from tests of 2 by 2-in. beams on a 28-inch span with the load in the center.[1]

Tensile Stress:

In general, the tensile strength of wood along the grain is little needed in the design of wood parts, and consequently very few data on this property are available. Furthermore, it is difficult to get reliable tensile tests along the grain because a slight deviation from parallelism with the grain suffices to cause failure by shear. Tensile tests across the grain can be satisfactorily made but the data are little used in aircraft design and have been omitted from Table I.

Torsional Properties:

Very little information exists on the torsional properties of the various woods used in aircraft, with the exception of spruce. Sufficient data are available, however, to indicate that the shearing stresses given in Table I may be safely used in design for the shearing stress at maximum torsional load without the reduction of 25 per cent used for longitudinal shear in beams. For example, 1000 lb. per sq. in. may be used for spruce in torsional shear instead of the 750 lb. per sq. in. given in the table for computing the resistance of beams to longitudinal shear. On the basis of 3 seconds duration of stress, the fiber stress at elastic limit in torsion may be taken as two-thirds of the shearing stress at maximum torsional load for any species.

The mean modulus of rigidity of spruce is equal to the modulus of elasticity along the grain divided by 15.5, or 84,000 lb. per sq. in. The ratios between these two moduli have not been obtained for other species, and until they are available, it is recommended that slightly higher ratios be used. Scattered tests show a range of values between 14 and 18.

Shrinkage of Wood:

Wood begins to shrink when all the free water has been removed from the cell cavities and the remaining moisture begins to come from the cell walls. As they dry, the wood continues to shrink in cross-sectional area until no more water can be extracted from it. Wood also shrinks longitudinally but this shrinkage is generally so small as to be negligible.

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[1] For a more complete discussion of variations in the modulus of elasticity see J. A. Newlin and G. W. Trayer, "Deflection of Beams with Special Reference to Shear Deformations," *Report No. 180*, National Advisory Committee for Aeronautics.

The shrinkage in cross-sectional area varies with different species and, like strength, is very closely related to specific gravity—the denser the wood the greater the shrinkage, generally speaking. Radial shrinkage, the shrinkage in width of edge-grain boards, averages about three-fifths as great as tangential shrinkage, the shrinkage in width of flat-sawn boards. The shrinkage values given in Table I are for the total change from a saturated to an oven-dry condition. The change is approximately lineal and by assuming a fiber-saturation point of about 25 per cent, shrinkage for a definite change in moisture content may be determined with fair accuracy. For example, the radial shrinkage of Sitka spruce dried from a moisture content of 14 per cent to 8 per cent would be about one-fourth of the value given in the table.

CHARACTERISTICS OF SOME OF THE COMMON AIRCRAFT WOODS

Spruce is by far the most important aircraft wood today. It combines the qualities of lightness, great strength, and stiffness per unit weight. It also has considerable toughness. Spruce dries well, works well, is easy to glue, and does not present any particularly difficult selection problem. It is very desirable for highly stressed parts, such as wing beams. Yet several important species, such as noble fir and Port Orford cedar, offer possibilities as a substitute for spruce in aircraft construction.

For such members as landing gear struts, which require great strength and stiffness or are to be steam bent, ash is commonly used.

When extreme lightness is desired, as for stream-lining, filler material, or for core stock of plywood where insulation is desired, as in cabins, balsa is used. It is one of the lightest woods known.

Where a uniform texture, hard finish, and resistance to wear are desired, birch, beech, and maple are exceptionally suitable. The sweet and the yellow birches are also among the most desirable of our native species for high-speed propellers. Maple, too, is suitable for this use.

The true hickories are extremely tough and very strong. They are especially suitable for tail skids and the like, where great shock-resisting ability is required.

Low-density species, such as basswood, northern white and sugar pine, yellow poplar, and Spanish cedar, are especially suitable for core stock in plywood.

Mahogany, black cherry, and walnut are excellent propeller woods. They retain their shape well and are hard enough to resist wear. The oaks are also used for propellers, the white oaks usually being preferred to the red oaks.

SPLICING AND JOINING WOODEN PARTS

When good design permits, the most practical and effective method of joining wooden aircraft members and parts is by gluing them. The plain scarf joint, the most suitable for splices, will give an efficiency of over 90 per cent in tension, compression, or bending, with a slope of scarf of 1 in 10. The efficiency of a glued joint is dependent not only upon the quality of the glue but even more upon the technique of gluing.[1] On account of the variations in effectiveness of gluing a flatter slope, such as 1 in 15 or 1 in 20, is recommended for tension splices, with a further recommendation that splices in beams be located away from the points of maximum moment.

The strength of a joint made by gluing the face of a relatively thin piece of wood at right angles to that of another piece (side grain to side grain) is controlled by the "rolling shear" strength of the wood; the allowable joint stress may safely be taken as one-half the shearing strength of the wood parallel to the grain. If secondary bending stresses accompany the usual tension or compression stresses at such a joint, the unit shearing stress on the glue area for design should be not greater than one-fourth the shearing strength of the wood parallel to the grain.

The attachment of metal parts and wires to wooden members is best obtained by means of metal fittings and bolts, the number and the size required at a given fitting being dependent upon the direction, with respect to the grain of the wood, of the line of action of the forces involved. A complete discussion of the attachment of metal parts and wires to wooden members is not within the scope of this paper. Let it suffice to say that design data are available with which the bearing strength of wood under steel aircraft bolts may be calculated.[2]

CONCLUSION

Wood has been the pioneering material in aircraft construction. Its exceptional advantages for small sizes and experimental types are unquestioned, and it continues to be one of the major materials of commercial aircraft development. With improvement in the methods of selecting and manufacturing the lumber and continued improvement in the fabrication methods there is every reason to think that wood can be used for aircraft on a mass production basis.

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[1] T. R. Truax, "The Gluing of Wood," *Bulletin No. 1500*, U. S. Department of Agriculture.

[2] G. W. Trayer, "Bearing Strength of Wood Under Steel Aircraft Bolts and Washers and Other Factors Influencing Fitting Design," *Technical Note No. 296*, National Advisory Committee for Aeronautics.

[For Discussion on Wood in Aircraft Construction, see page 181.—ED.]

AERONAUTICAL TEXTILES[1]

By W. E. Emley[2]

Synopsis

Textiles are used in the aeronautical industry for the coverings of balloons and the wings of airplanes, for the gas cells in balloons and for parachutes. The properties of the fabrics required for these purposes are described. A coated cotton fabric is now being used in place of goldbeater's skin for gas cells and cotton is now replacing silk for parachutes.

The fabrics usually considered as coming under the designation of aeronautical textiles are balloon cloth, gas cell fabric, wing fabric, and parachute fabric. Of course, textiles are used to a great extent by the aeronautic industry for purposes which are not peculiar to that industry, such, for instance, as ropes, insulation for wires, upholstery and tire cords.

For obvious reasons, the chief desideratum in all aeronautical textiles is maximum strength with minimum weight. In addition, certain other properties are important for specific uses.

Balloon Cloth

Balloon cloth is a plain woven cotton fabric which is used either as such or as the basic material for making plied and coated fabrics for many purposes in the construction of balloons and airships. It has also found wide use in other industries, so that balloon cloth is now considered a standard article like sheeting or muslin.

There are several grades of balloon cloth which differ from one another in weight, thread count, and strength. They are all "square-woven" (have the same number of threads per inch in both warp and filling direction). The "HH" grade is perhaps the one in most general use. This has 120 threads per inch in each direction, a tensile strength of 38 lb. per inch of width in each direction, and a weight of 2.05 oz. per sq. yd.[3] See Navy Specification 27C13 (November 1, 1929) or Army Specification 6–39–C (August 25, 1927) for complete descriptions of the "HH" grade and other grades.

For the different parts of the balloon or airship, the balloon cloth may have to be rubberized (coated with a thin layer of rubber vulcanized in place) to make it air tight or gas tight. Fabrics of two or more layers may be built up and the layers may be cut straight or on the bias to give desired properties. The outside layer may be coated with aluminum, applied as a paint, to minimize absorption of heat and the destructive effect of light on the fabric. The make-up of several of these fabrics, designed for different purposes, is described in Army Specification 6–44–D (September 5, 1927).

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[1] Published with the approval of the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Chief, Division of Fibrous and Organic Materials, U. S. Bureau of Standards, Washington, D. C.

[3] All weights given are for the fabric conditioned at 70° F. and 65 per cent relative humidity.

GAS CELL FABRIC

The gas (hydrogen or helium) used to give buoyancy to an airship is contained in cells inside the ship. The walls of these cells must be impervious to the gas, to prevent undue or unintentional loss. A method for testing the permeability of fabrics to hydrogen was worked out by Edwards.[1]

Goldbeater's skin cemented to cotton cloth was formerly used for gas cell fabric, but of late a rubberized fabric built up of balloon cloth has been coming into favor. For this fabric to be sufficiently impervious to gas, it must be quite heavy. A new process, whereby a single ply of rubberized balloon cloth is coated with a mixture of viscose and rubber latex, has given promising results. See U. S. Patent 1,665,500.

WING FABRIC

The fabric used in covering the wings of airplanes is a plain-woven mercerized cotton cloth. It has 80 two-ply threads per inch in each direction (warp and filling), has a tensile strength of 80 lb. per inch of width in each direction, and a maximum weight of 4.5 oz. per sq. yd.[2] For other properties, and tolerances, see U. S. Government Master Specification No. 258*b* (January 25, 1929).

After the wings are covered, a dope is applied which shrinks the fabric to the desired tautness and which thereafter protects the cotton against changes in area (and therefore in tautness) which would occur if the bare fabric were exposed to the varying humidity of the atmosphere. This dope is a solution of cellulose acetate or nitrate in a volatile solvent, to which a plasticizer has been added.

PARACHUTE FABRIC

The design of parachute fabric is in a state of flux, there being three fabrics now in use for making parachutes.

The oldest is a plain-woven silk fabric, having 120 threads per inch in the warp and 90 in the filling, a tensile strength of 45 lb. per inch of width in each direction (40 lb. per in. in warp and 50 lb. per inch in filling) and a weight of 1.55 (1.45) oz. per sq. yd. These figures are taken from Navy Specification C-37*a* (April 25, 1929); the figures in parentheses from Army Specification 7-8-G (February 1, 1929). Reference should be made to both specifications for other requirements and tolerances.

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[1] J. D. Edwards, "Determination of Permeability of Balloon Fabrics," *Technologic Paper No. 113*, U. S. Bureau of Standards.

[2] All weights given are for the fabric conditioned at 70° F. and 65 per cent relative humidity.

It was found that a modified basket weave produces a fabric which has a higher resistance to tearing than a plain-woven fabric. This fabric has 96 threads per inch in the warp, 105 threads per inch in the filling, a tensile strength of 53 lb. per inch in each direction, and a weight of 1.70 oz. per sq. yd. The basket weave is covered by patent No. 1,650,998.

More recently, the Bureau of Standards and the National Advisory Committee for Aeronautics have been trying to develop a cotton fabric suitable for this purpose. The experiments have not yet reached the point where such a fabric can be officially recognized by the military branches of the Government. For commercial purposes, however, cotton parachutes are now on the market and the number in use is rapidly increasing. They are a little heavier and more bulky than silk, but their lack of resilience, which was one of the chief obstacles to their use, has been overcome by the general use of a pilot parachute or other self-opening device.

PROPERTIES OF COTTON

The design of aeronautical textiles has reached, and sometimes surpassed, the limit of our ability to handle cotton. Further development depends upon our finding how to make a fabric having greater strength with less weight. Good balloon cloth has a strength-weight factor of 20; that is, the strength in pounds per inch of width (40) is 20 times the weight in ounces per square yard (2). This is about the best that has been done in commercial production with home-grown cotton. Cotton produced elsewhere (notably Egypt) has a longer and softer fiber, which can be used to produce a fabric having a slightly greater strength-weight factor. Here also we are handicapped by the fact that few mills in the United States are equipped to spin the very fine yarns (120's or finer) which are required. While an industry might be built up on imported raw cotton or imported yarn, even with these it is not now possible to improve very greatly on good balloon cloth. For a strength-weight factor of 29, such as was formerly required for parachutes, we must resort to silk.

Cotton yarn has only about 20 per cent of the tensile strength of the fibers of which it is composed. If some method of improving this "spinning efficiency" could be devised, it would be a great boon to aeronautical designers, as well as to the cotton industry.

CORROSION-PREVENTION METHODS AS APPLIED IN AIRCRAFT CONSTRUCTION[1]

By H. S. Rawdon[2]

[Editor's Note.—The subject of corrosion-prevention methods discussed in this paper is also treated in part in a paper by H. A. Gardner entitled "Notes on Aircraft Finishes," included in this Symposium, see page 68.]

Synopsis

Based on information supplied by leading aircraft manufacturers, a résumé of present commercial practice on corrosion-prevention methods in use has been prepared. The survey shows that the Army and Navy requirements are doing a great deal to bring about uniformity in commercial practice.

Whenever practicable, all steel structural parts are plated, either with cadmium or zinc. This is followed by an iron-oxide primer and a lacquer or enamel of some kind. The inside of closed tubular members is filled with raw linseed oil, drained, and sealed. Open-end tubular members are coated inside with the iron-oxide primer.

Navy practice requires duralumin to be treated by the anodic-oxidation process prior to the application of a priming coat, as on steel, to be followed by the finish coating. In Army practice, very careful preliminary chemical cleaning of the surface is required to be followed by a priming coat and finish coats. Commercial practice appears to follow the Army practice somewhat more closely than that of the Navy.

Special mention is made of prevention of "crevice" corrosion, and the importance of preliminary treatment prior to coating. Corrosion-resistant steels are used only to a very limited extent in the aircraft industry.

Introduction

In order to secure reliable information which would serve as the basis of a report on methods of corrosion-prevention in current use in aircraft construction, letters were sent to leading manufacturers soliciting such data. The response to the requests was very gratifying indeed, replies to over 75 per cent of the 31 sent out having been received. The compilation of the information thus secured may confidently be accepted as summarizing current industrial practice.

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[1] Published with the approval of the Director of the Bureau of Standards of the U. S. Department of Commerce, Washington, D. C.

[2] Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.

In addition, the replies are of particular value in that they show that the practice is tending to become fairly uniform. The requirements of the Air Corps of the U. S. Army and of the Bureau of Aeronautics of the Navy Department as set forth in their specifications and contracts awarded have, unquestionably, tended to set a standard for the industry in this country although the "standard" is by no means a fixed one as yet. A digest of the contents of all the replies received is deemed unnecessary since deviations from the requirements designated here for purposes of convenience as "standard" are distinctly confined to items of relatively secondary importance.

The metals to be considered in this discussion are steel and aluminum (including its alloys). None of the other light alloys, such as magnesium, enter into construction to any great extent, at least for purposes in which the resistance to atmospheric corrosion is important.

PROTECTION OF STEEL PARTS

With but very few exceptions, electroplating of all steel structural parts is the rule, the size of the parts used being the principal limiting factor. However, plating is expressly forbidden on hollow parts in which the plating solution may be entrapped and retained because of difficulties in draining. Both zinc and cadmium plating, deposited directly on the steel, are used, the preference being apparently somewhat in favor of cadmium. Cadmium plating is required by the Navy in its contracts.[1] The quality of the plated coating is insured by the requirement, in Navy specifications, that such plated articles must withstand an exposure of 200 hours in the "salt spray" without a breakdown of the coating such as would be shown by rusting of the steel base. According to the U. S. Army Air Corps requirements[2] the zinc coating should be not less than 0.001 in. in thickness, an average thickness of 0.0015 in. being desired. The cadmium coating should be not less than 0.0003 in. in thickness. It may be inferred, therefore, that coatings whose thickness is equal to the minimum allowed in each case will successfully withstand the exposure of 100 hours in the salt spray required by Army specifications. The threads on threaded parts which are zinc-plated are undercut, usually 0.002 in.; this is not necessary if cadmium plating is used.

In general all steel parts are coated after plating. A priming coat, of which the composition given below is typical, is first applied:

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[1] Bureau of Aeronautics, Instructions for Finishing Naval Aircraft, SR-15, April 21, 1930.

[2] U. S. Army Specification No. 3–100A, February, 1927, superseding No. 3–100A, July, 1926

COMPOSITION BY WEIGHT OF RED OXIDE PRIMER.

Neutral red oxide of iron	40 per cent
Zinc chromate	20 "
Boiled linseed oil	30 "
Turpentine	8 "
Japan drier	2 "

A "finish" coat is applied to the primed surface after drying. In case the steel was not plated, two applications are ordinarily required. Although this coating may vary somewhat in different cases, its general nature is not widely different. A water-resisting spar varnish usually forms the vehicle; the pigment may differ somewhat. Navy gray enamel (spar varnish pigmented with white lead) and aluminum pigmented spar varnish are often specified. Nitrocellulose lacquers, although somewhat softer than other types of lacquer, have been found to be very durable in tests carried out by the Army Air Corps.

The methods used for protecting the inside surfaces of tubular steel parts are practically the same throughout the industry. Closed steel tubular members, such as fuselage frames, are filled with hot (approximately 160° F.) raw linseed oil under slight pressure and allowed to drain thoroughly. The holes, drilled for the purpose of filling and draining, are then tightly sealed by special plugs screwed securely into place. This procedure is, of course, carried out after all operations involving heating have been completed. The use of a hot "rust preventive" for this purpose as an alternative for linseed oil was reported in a few cases. For protecting the inner surface of open-end tubular parts, such as struts, braces, aileron bars, and similar members, the treatment just described is not used. An oil which will set more rapidly than linseed oil may be used instead. The use of such an oil on both interior and exterior surfaces, in place of a primer, was reported by one manufacturer. In most cases, however, a primer such as is used as the first coat on external surfaces was mentioned in most of the replies as the means used for protecting the inside of open-end tubular steel parts. (The same method is applied to duralumin tubing.)

Standard parts such as shackles, pins, nuts, bolts, and other fasteners (previously plated) are coated after the assembling has been done. They are usually given a coating of the same kind as the final coating used on other steel parts. Control cables, the constituent wires of which have been tinned, are thoroughly coated with oil, sometimes by immersion in hot linseed oil. In addition, a grease coating of some kind is used just after or just prior to installation.

PROTECTION OF ALUMINUM AND ALUMINUM-ALLOY PARTS

The materials to be considered are aluminum and high-strength aluminum alloy of the duralumin type. Most of the parts by far of this material are fabricated from sheet, although a considerable amount of tubing is also used.

There is less uniformity in the methods used for the surface treatment of aluminum than for steel.

The Navy practice, as represented by the Naval Aircraft Factory, is to apply the anodic-oxidation process to all parts whose size will permit, a 3-per-cent by weight aqueous solution of chromic acid being the electrolyte used. This is also required in all contract work for the Navy.[1] The process is not applied to alloys having a copper content greater than 5 per cent. Only two other replies indicated that the anodic-oxidation process was used as a regular treatment. One of these, from a manufacturer of seaplanes, reported that the process is applied to the "Alclad" duralumin parts after fabrication (plain duralumin not being employed by this manufacturer) primarily in order that the rivets would receive the benefit of the treatment. The few other replies reporting the use of the anodic-oxidation process indicated that it was used only to a limited extent, for example, on small castings, aluminum lines in the cooling system, trailing edges of duralumin parts, etc.

The Naval Aircraft Factory has not found the anodic treatment to be applicable to aluminum alloy castings in general, however, on account of the variable shape and relatively large size.

The Jirotka process, which is somewhat akin to the anodic-oxidation process in the character of the results produced, was mentioned in two cases, representing both Army and Navy contracts, for the first treatment of aluminum fuel tanks. In brief, this process consists in the formation of a very uniform and thin surface film, presumably oxide, by immersion in a solution, the composition of which is rather complex and which may vary but which always contains a chromate.

In all the above cases the surface treatment of the aluminum is intended only as a preliminary one, to be followed by a series of coatings, usually identical with respect to the primer, at least, with that used on the steel parts. An aluminum-pigmented bitumastic coating has been found by the Navy to be very suitable for "all round" general use where abrasion is not a very serious factor. By many, the coating applied over the priming coat is identical with that used on steel. In case no preliminary treatment, such as the anodic-oxidation process, was used, the necessity for a very careful cleaning (including a slight roughening) of the surface prior to the application of the coating was emphasized in most of the replies. It is of interest to note that the anodic-oxidation process has not hitherto been generally approved for duralumin rivets, that is before driving, although experimental work now in progress at the Naval Aircraft Factory indicates that it may be advantageous so to do.

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[1] *Loc. cit.*

In general, the "Alcald" type of sheet duralumin which is used on some large commercial airplanes is not given any protective coating in addition to the aluminum "skin" which forms an integral part of the sheet as rolled.

The duralumin type of alloy as an aircraft construction material is of course most widely used for lighter-than-air craft. In those cases in which the aluminum-clad sheet duralumin has been used, such as the hull of the airship ZMC-2, further protective measures have not been considered necessary. Plain duralumin has in all cases been given the anodic-oxidation treatment to be followed by a sprayed coating of aluminum-pigmented spar varnish or in some cases (for interior parts) a greasing with lanoline.

For the inside surfaces of floats, the aluminum-pigmented bitumastic coating has been used considerably in Navy practice and for the outside surface a red-oxide priming coat followed by two coats of Navy gray enamel. According to one manufacturer, this type of finish has proved exceptionally resistant even after two years of marine service. One of the manufacturers of seaplanes reported that excellent results are being obtained from the floats made of aluminum-coated duralumin ("Alclad") which has been given the anodic-oxidation treatment, primarily for protecting rivet heads without any other protective coating. Another manufacturer reported the use of the iron-oxide primer and aluminum-pigmented enamel (one coat of each for the interior of floats).

SPECIAL PRECAUTIONS

Crevice Corrosion:

In the treatment of any metal structure for corrosion prevention, special attention should be given to the possibility of "crevice" corrosion, since it is from such an attack that the greatest damage usually results rather than from the attack on relatively large open areas. Not only is the extent to which such an attack may have progressed often almost entirely concealed from inspection, but the rate of the corrosive attack in a crevice, as explained by Evans[1] on the basis of an oxygen-concentration cell, is often very much greater than elsewhere on the same structure. In many of the replies received a number of special precautions having a bearing on this point were mentioned. A few typical examples are as follows: Contact between metal parts, such as the fuselage, and wood, leather, etc., which might absorb and hold water, is prevented by placing rubberized balloon tape, bitumastic paint or something similar between the two. The practice of coating the metal parts which may be in contact with wood, *before* assembly, is quite generally followed. Surfaces in contact with doped fabric are covered with "dope proof" paint or aluminum foil on top of the protective coating already applied. Although this is done primarily to prevent injury to the doped fabric, it also is to be recommended from the corrosion standpoint. Duralumin and steel parts before being assembled by riveting or bolting, especially if in contact with a dissimilar metal such as brass or bronze, are usually given a coating of primer or Navy gray enamel on the contact surfaces; likewise duralumin rivets are often wetted with the iron-oxide paint or sometimes with Navy gray enamel immediately before driving. This insures water-tightness and thus incidentally guards against crevice corrosion.

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[1] U. R. Evans, "Corrosion of Metals at Joints and Crevices," *Engineering*, Vol. 123, p. 362 (1927); also *Journal*, Royal Soc. Arts, Vol. 75, p. 544 (1927).

Surface Preparation Prior to Coating:

The efficiency of any "protective" coating is dependent upon its adherence to the surface and, further, the degree of adherence is related to the preliminary surface treatment. The necessity for the very careful preliminary cleaning and treatment of the surface prior to coating is apparently well recognized in the industry.

In the case of steel, the chemical cleaning necessary for successful zinc or cadmium plating, together with the plating operation itself, constitutes an admirable surface treatment. The information given on the methods for cleaning steel parts which were not plated was rather meager. In one case, sand blasting was specifically mentioned as being proper and suitable for this. A light sand blasting is also permitted by the Army regulations[1] in order to remove very adherent scale, as is also pickling in a hot acid solution followed by immersion in a weak alkaline bath. Usually, however, a hot alkaline cleaning solution or a grease solvent, such as gasoline, to be followed by a hot washing solution is deemed sufficient. It is often claimed that the nature of surface treatment and the thoroughness of the application are more important on aluminum and its alloys than on steels. Evidence to support this claim is lacking, however. The anodic-oxidation treatment for such materials, like plating for steel, is an excellent treatment to precede the application of a coating, and, as previously mentioned, this treatment is especially recommended by the Naval Bureau of Aeronautics. Experiments carried out by the Aluminum Company of America[1] have very conclusively demonstrated the decided advantage to be gained by such a treatment prior to the application of coatings, such as aluminum-pigmented spar varnish, even for very severe conditions such as repeated immersion.

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[1] U. S. Army Specification No. 3–100A, February, 1927, superseding No. 3–100A, July, 1926.

The cleaning of the bare surface of aluminum or an aluminum alloy generally consists in the use of a mild etching solution. A commercial cleaner consisting essentially of a dilute solution of phosphoric acid was reported in numerous cases to be very effective. Another permissible method consists of a "caustic dip" to be followed by neutralization with weak acid. A cleaning solution of sodium bichromate in concentrated sulfuric acid to be followed by thorough rinsing in hot water is permitted in the Army regulations. Slight roughening of the surface by mild abrasives as well as by wire brushing and even by sand blasting for heavier parts was reported as being an approved method, each to be followed by chemical cleaning of some kind. It is of interest to note that cleaning of aluminum surfaces by pickling, caustic dip or sand blasting is strictly forbidden in the latest Navy instructions.[2]

Corrosion-Resistant Steels:

In general the use of corrosion-resistant steels is very limited. Such uses as were reported were often as much on account of the non-magnetic properties of the steel as its corrosion-resistance. Some uses reported were exhaust stacks, swivel joints at movable strut ends, cowl pins and other cowl fasteners, hoisting slings on Navy planes, streamline wire, control chains, movable parts of column control and the like.

Copper or Brass:

No coating is required on copper or brass parts, except possibly for decorative purposes. If in contact with aluminum or duralumin, tinning of the copper or brass is considered necessary.

Acid-proof Coatings:

On all metal parts near the battery in an airplane, an acid-proof coating is required. In general this applies to those parts within a radius of 10 to 12 in.

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[1] Private communication from C. F. Nagel, results unpublished as yet.

[2] *Loc. cit.*

[For Discussion on Corrosion Prevention, see page 184.—ED.]

NOTES ON AIRCRAFT FINISHES

BY H. A. GARDNER[1]

SYNOPSIS

This paper discusses various types of wing dopes. The suitability of acetate as compared with nitrate dopes, and the desirability of pigmenting dope is outlined. The possibility of producing pre-doped fabrics is also discussed. The results of extended exposure tests of doped surfaces are outlined.

The coating of steel parts on aircraft is given considerable attention. The plating of metal and subsequent finishing systems are described. The necessity of including integral coatings on tubing to prevent corrosion, and the possibilities of varnish coatings in place of linseed oil are pointed out.

The results of extended tests on the coating of duralumin, a metal which must be treated differently from steel, are presented. The value of anodic coatings or other surface treatments on duralumin, previous to the application of distensible oil or varnish coatings, is indicated. Methods of treating duralumin pontoons and hulls are described.

WING DOPES AND FABRIC FINISHES

Plywood wing surfaces are used to some minor extent. They may be preserved with a pigmented oil primer, sanded, and then given one coat of dull and one coat of gloss pigmented four-hour varnish enamels. Excellent durability will be obtained. While corrugated duralumin has been used during recent years to some extent, the majority of planes are still covered with fabric. It is true that metal covering is being used to an increasing extent because of its strength and permanent tautness, but it is probable that fabric will continue in use because of its lower cost, availability and ease of application. During 1925 and 1926 the author conducted a series of tests in cooperation with the Bureau of Aeronautics to determine the effects of various doping schedules upon airplane fabric surfaces. A set of doped fabric-covered panels were exposed at Pensacola, Fla., for 90 days, and another set in Washington for a period of 180 days. The object of the tests was to determine whether clear dopes or pigmented dopes would give the greater durability and whether varnish, pigmented varnish, or pigmented dope would give the best service over the clear or pigmented undercoats of dope. Thirty-nine different doping systems were used in these tests, and the best results were obtained with schedules Nos. 8, 10 and 33. The results of the tests with these three doping schedules are outlined in Table I.

It was noted in these tests that whenever acetate dope was used for the priming coat, lower tautness was generally evidenced, although good strength was developed. Whenever nitrate dope was used for the priming coats good tautness was shown, and satisfactory strength obtained. In fact, the whole series of tests indicated that when nitrate dopes were applied and properly protected from light by aluminum-pigmented outer coats, the underlying coats of nitrate dope were not broken up by sunlight, the strength of the fabric was maintained, and excellent tautness effected. Dopes pigmented in colors other than aluminum gave satisfactory service, but they are usually of greater weight.

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[1] Chemical Engineer, Institute of Paint and Varnish Research, Washington, D. C.

TABLE I.—EFFECTS OF THREE DOPING SCHEDULES UPON AIRPLANE FABRIC SURFACES.

	Schedule No. 8 4 Coats Nitrate Dope and 2 Coats Aluminum Nitrate Dope	Schedule No. 10 1 Coat Clear Acetate Dope, 3 Coats Clear Nitrate Dope and 2 Coats Aluminum Varnish	Schedule No. 33 4 Coats Clear Nitrate Dope and 2 Coats Aluminum Nitrate Dope with $\frac{1}{2}$ Usual Aluminum Content
Weight of Finished Fabric, oz. per sq. yd.	7.9	7.7	7.9
Average Tensile Strength, lb. per inch of width:			
Before exposure	99	95	89
After exposure at Washington 6 months	69	80	90
After exposure at Pensacola 3 months	90	92	86
Tautness by Finger Test:			
Before exposure at Washington	Remarkable	Very good	Remarkable
After exposure at Washington	Excellent	Very good	Very good
Before exposure at Pensacola	Excellent	Good	Remarkable
After exposure at Pensacola	Excellent	Very good	Good
Appearance of Fabric:			
After exposure at Washington	Very good, flexible	Very good, flexible	Very good, flexible
After exposure at Pensacola	Very good, no defects visible, flexible	Very good, high gloss, flexible	Very good, flexible
Tautness[a] After Exposure at Pensacola (Freymoyer-Barnaby Apparatus)	30	21	27

[a] Tautness figures denote number of hundredths of an inch spring deflection required to depress center of panel 0.1 in.

Since acetate dopes are relatively expensive as compared to nitrate dopes, and since entirely satisfactory results were obtained in these schedules with nitrate dope, it is probable that acetate dope could be done away with as a primer, and only nitrate dope used. As a matter of fact, the Navy Department has apparently discontinued the use of acetate dope, satisfactory service being obtained with the nitrate. This could be applied in four-coat work in the clear to develop the requisite tautness. Two coats of the same type of dope pigmented with aluminum powder to shut out the ultra-violet light could then be applied.

Aluminum-pigmented dope presents such a rough surface that it soils very quickly and picks up grease and dirt that cannot readily be removed from wing surfaces, even when scrubbed. For this reason, air station mechanics desire a smooth, washable surface that can readily be cleaned. To accomplish this two thin coats of clear spar varnish may be applied over the aluminum pigmented dope. If the varnish is of fairly light color, it does not cut down the reflectivity of the surface to any marked degree. It is true that clear varnish is not durable over extended periods of exposure, and when used should preferably have sufficient pigment to give protection against light.

For the production of pigmented varnishes to use for flag or special insignia colors on doped fabric, there is usually applied a spar varnish to which has been added sufficient light-weight pigment ground in raw linseed oil to a stiff paste. A small amount of turpentine may be added to reduce the viscosity of the mixture. These pigmented varnishes produce very satisfactory results over nitrate-doped surfaces. When applied over acetate dope, the adhesion is very often unsatisfactory, and scaling may be observed. Such light-weight pigments as toluidine red are usually applied when a bright-red flag color is desired. For white, low density but highly opaque white pigments should be used. The white may be tinted gray with lampblack where a gray is desired, and with Prussian blue where a blue flag color is desired. Where a canary color is desired, which is often used upon the West Coast, zinc chromate or cadmium yellow may be the tinting color for the white base. In case of forced landings at sea, such colors would be of high visibility and would attract the notice of relief parties. The color could also be used in the finishing coats of dope.

LACQUER

Properly compounded nitrocellulose lacquer coatings are now being applied to the top side wing surfaces. The chief disadvantage of lacquer coatings on fabric is lack of flexibility. However, as yet very little cognizance has been given to the newly developed lacquer-varnish coatings. These coatings usually contain nitrocellulose properly compounded in solution with phthalic anhydride-glycerin resins. They are quick drying in nature and produce finishes which are highly water resistant. Their durability is exceptionally good. Exposure usually results in a chalky film which is ideal for repainting. It is believed that these new type lacquer-varnishes, when pigmented, would make excellent coverings for the top sides of the wing surfaces and for general use on other plane equipment.

COATINGS FOR STEEL PARTS[1]

Corrosion of steel and iron fittings on aircraft is apt to be very serious unless the most durable types of protective coatings are applied.

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[1] For further discussion of this subject, see paper by H. S. Rawdon, on "Corrosion-Prevention Methods as Applied in Aircraft Construction," p. 61.

The metal should be cleaned, preferably by sand blast, and primed with low-weight zinc chromate - iron oxide mixtures. They may then be coated with aluminum varnish or Navy gray enamel.

Whenever practicable, it has been recommended that steel parts, except tubing, should be cadmium plated. It has usually been the practice, however, to refrain from plating the tubes because of the difficulty of washing out the interior parts after the plating operation. The presence of a small amount of pickling liquor left in the tubes might start active corrosion. Cadmium-plated surfaces which will withstand a 100-hour test with a 20-per-cent salt spray solution are desirable. Immediately after plating, washing, and drying, all parts should be given a coat of primer. The application of the primers at this early stage may prevent the metal being spotted with grease in handling; grease spots prevent good adherence of subsequently applied coatings. While tubing is generally pickled to prepare the surface for the application of protective coatings, sand-blasting of all other metal surfaces is probably desirable. Wherever pickling is done, the acid should be well drained from the tubes and the tubes rinsed thoroughly with cold water and then for several minutes in a bath containing hydrated lime in order thoroughly to neutralize any traces of acid which may be left in the tubes. The use of lime after pickling metal surfaces which are to be painted was found advantageous on several hundred large-size steel and iron panels which the author used in the series of paint tests conducted in cooperation with the American Society for Testing Materials in 1910 at Atlantic City.[1] After this treatment, the metal plates were found to be in an excellent condition for painting at the time they were removed from the lime storage boxes.

At the present time, linseed oil, forced in under pressure, is used as a protection for the inside of tubular members. Cooked mixtures of tung oil and resin usually produce films which are much more water-resisting than linseed-oil films, and for this reason proprietary compositions made from tung oil suitably combined with resins to produce quick-drying, tough coatings, are to be advocated in place of raw linseed oil. The use of some pigmentary substance of a rust inhibitive nature, with the tung oil filling compounds, increases the resistance of the films to moisture penetration. The filling holes in the tubes are later spot-welded.

Some of the recommendations of J. E. Sullivan[2] for preventing corrosion of aircraft parts are as follows:

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[1] Report of Joint Subcommittee, of A-5 and D-1, in Charge of Erection and Painting of Steel Test Panels at Atlantic City, *Proceedings*, Am. Soc. Testing Mats., Vol. X, p. 79 (1910).

[2] "Combating Corrosion on Aircraft Metal Parts," *Aviation*, February 1, 1930.

1. Thoroughly clean and dry all surfaces prior to the application of protective coatings. The initial specified finish coat should be applied as soon as practicable after the parts have been cleaned.
2. Paint all faying surfaces before assembly.
3. Bake on the finish when practicable.
4. Control cables should not be painted but coated with a mixture of white lead and tallow. The proportion by weight is 50-50.
5. The use of lacquer as a protective coating on aircraft parts, particularly fabric and metal surfaces, is not recommended. Better protection can be obtained by the use of more distensible coatings.
6. Avoid contact of wood and metal. Wood, in view of its hygroscopic nature, retains moisture if it becomes wet and if in contact with metal will ultimately cause corrosion of the metal. If these materials must be used, insulate by coating the faying surfaces of both the metal and the wood with marine glue or bituminous paint and aluminum foil.
7. Avoid contact of dissimilar metals.
8. Apply an anti-seize compound made up by weight of 50 per cent petrolatum and 50 per cent zinc dust to threaded parts.
9. Always use corrosion-resisting metals where possible.
10. In employing heat-treated duralumin, quench the material in cold water. Quenching in this medium gives the metal greater corrosion-resisting qualities than can be obtained if a hot water or air quench is used

PROTECTIVE COATINGS FOR DURALUMIN[1]

Among the problems that must be considered in connection with the protection of duralumin is its high coefficient of thermal expansion, as compared with steel. Certain types of quick-drying coatings that would be suitable on steel surfaces, may not be sufficiently distensible for use on duralumin. Similarly, it has been found that coatings which stand up satisfactorily on duralumin may not always function efficiently on steel. During 1926 the author exposed a large number of panels of duralumin coated with several different protective coatings, to determine the type that would adhere satisfactorily and protect the metal from the corrosive effects of the atmosphere. During the spring of the year previous to starting the tests, the author made an inspection of an old Junker plane made almost entirely of duralumin, including all wing surfaces. This plane, upon completing its service, had been placed upon the sand dunes at Hampton Roads, and some clear and pigmented spar varnish coatings and a bituminous solution had been applied to the topside wing surfaces for test purposes. Six months after exposure, the surface coated with a heavily pigmented spar varnish showed a powdery surface and some scaling. The clear varnish had almost disappeared. The bituminous solution had alligatored and powdered. The aluminum spar varnish had stood up fairly well. One section of the surface had been lettered with lampblack oil color to indicate the areas upon which the test paints had been applied. At the time of inspection, the letters were in an excellent state of preservation. This suggested that lampblack in oil, because of its great elasticity, might stand exposure on duralumin for a long period of time. Accordingly, there was included in the panel tests a coating made with such a product, and excellent serviceability was secured.

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[1] For further discussion of this subject, see paper by H. S. Rawdon, on "Corrosion-Prevention Methods as Applied in Aircraft Construction," p. 61.

Panels for the test were obtained through the Bureau of Aeronautics from the Naval Aircraft Factory at Philadelphia and through the War Department from McCook Field. After finishing, one set was exposed in Washington and another set at the submarine base at Hampton Roads, the latter panels being placed on a rack extending over the surface of the ocean so that the panels would, at high tide, receive a certain amount of salt water spray during stormy weather While only a few months were required to secure failure in a great many cases, the final results of the exposures, which extended in some instances up to two years, could be summarized as follows:

1. Clear nitrocellulose or clear varnish coatings upon either duralumin or steel were broken down quite rapidly when exposed under the trying conditions which prevailed in these tests. When either of these types of coatings are mixed with pigments which shut out ultra-violet light, results indicating very much greater durability are obtained.

2. Basic pigments may be included as component parts of protective coatings for duralumin and similar light-weight alloys, with highly satisfactory results.

3. It is apparent that linseed-oil paints, because of their great flexibility, are exceptionally well suited for the protection of duralumin. Because of the low weight of such coatings when pigmented with black carbon pigments or with aluminum powder, it is believed that where weight is a factor, such types of paint are well suited for the purpose. Aluminum powder greatly retards the drying of raw-oil paints. The addition of basic white pigments or the use of boiled linseed oil is suggested.

4. Where tung-oil spar varnish is applied as a medium for dispersing black pigments or aluminum powder, it is suggested that the varnish be of a very long oil type, as previous tests have indicated the durability of such paints when exposed with an elastic long-oil vehicle.

As a result of these tests, the author later designed a primer for duralumin, which consists of zinc chromate and red iron oxide, two pigments which gave excellent results in the above described tests, finely ground to a stiff paste in linseed oil to give elasticity, and then reduced with varnish and drier to a thin consistency so that when applied to duralumin surfaces a fairly quick-drying coating would result. This formula was later adopted by the U. S. Navy Bureau of Aeronautics and has been in successful use for a period of several years. It will withstand baking at a temperature of 250° F. for a period of one hour with satisfactory results, and when so treated produces a semi-dull, elastic film over which pigmented oil varnish coatings or nitrocellulose lacquers may be applied. Fortunately a rather broad-minded policy has been developed in regard to duralumin primers. The necessity of not retarding contractors in production schedules by the use of slow drying primers is a matter that has often been given proper consideration by the governmental authorities.

While it is probable that aluminum and duralumin will not deteriorate very seriously on land planes, rapid corrosion may take place on seaplanes in warm climates and where contact with salt water is frequent. The preparation of the metal surface for receiving protective coatings is very important. Apparently it has been found that the anodic treatment with chromic acid gives the best surface preparation. J. D. Edwards has brought to the author's attention the work of Bengough and Sutton,[1] from which it is apparent that there could be recommended a 3-per-cent solution of chromic acid free from sulfates or sulfuric acid and maintained at a temperature of 40° F. The aluminum as anode is subjected to a voltage which is gradually raised from zero to about 50 volts over a period of one hour. The schedule used is to increase the voltage from 0 to 40 volts in the first 15 minutes, hold it at 40 volts for 35 minutes, then increase to 50 volts over a period of 5 minutes, hold for another 5 minutes, and finally remove, wash and dry the article. With the copper alloys, such as duralumin, it is considered that the maximum potential should not exceed 50 volts. Graphite cathodes have been used satisfactorily.

As a priming coat over anodically-treated aluminum and duralumin, the zinc-chromate - iron-oxide elastic primer previously referred to may be used. The Bureau of Aeronautics now specifies anodic treatment on all production work involving the use of aluminum alloys. These anodically-treated surfaces are subsequently treated with chrome primers and finished with aluminum enamel or Navy gray enamel. When the primer is used, baking at 250° F. for an hour produces a firm finish. In order to aid production in rush times, coatings which dry in this period under baking temperatures are, of course, desired. Moreover, the finish formed is suitable for the application of some types of nitrocellulose lacquers, as well as oil varnishes.

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[1] G. D. Bengough and H. Sutton, *The Metal Industry* (London), Vol. 29, pp. 153, 175 (1926); *Engineering*, Vol. 122, p. 274 (1926).

It has also been brought out that aluminum bituminous paints have proved satisfactory over anodically-treated aluminum alloys, but these preferably should be used on surfaces that are not to be exposed to sunlight. These aluminum-bituminous solutions have also been used satisfactorily for the interiors of pontoons where much corrosion is apt to occur. This type of coating is very water resistant and suitable where it is not exposed to the sun. In strong sunlight, alligatoring, dulling, and destruction of the film may take place in brief periods. One disadvantage of bituminous paint is its solubility in gasoline. For this reason, gasoline-resistant coatings, made usually with shellac, have been employed on certain surfaces which may come in contact with gasoline.

The exterior of duralumin pontoons and flying-boat hulls may be treated with a coat of zinc-chromate - red-oxide primer and two coats of aluminum spar varnish, but if the hulls are to be moored for any undisturbed period of time in waters which are infected with barnacles, they should be surfaced with anti-fouling compositions.

Exhaustive studies on the protection of aluminum and magnesium aircraft alloys have also been made by the subcommittee on metals, of the National Advisory Committee for Aeronautics. Extensive exposure tests at Coca Solo and other points, representative of atmospheric corrosive conditions of different intensity, have been conducted, and the importance of providing continuous coatings for these materials has been pointed out. In connection with the development of coatings for magnesium alloys, it is of interest to point out that the committee has under test a number of spar varnishes, rubber paints, and vinyl acetate coatings. It would appear that they have found that a phosphate treatment of the surface of the metal previous to the application of the organic coatings is often desirable in order to increase the adherence of the coating.

MISCELLANEOUS NOTES

In connection with the varnish which is now used on aircraft, in clear and pigmented form, for coating fuselage, landing gear, wood ribs, spars, plywood, and top-side wing surfaces, it is of interest to point out that the specifications under which this varnish is purchased by governmental agencies were written several years ago. Unfortunately these specifications have not kept pace with modern developments in varnish production. Thus, for instance, it has been proved by a great many tests made throughout the United States during the past three years, including tests recently published by the Bureau of Standards,[1] that tung oil varnishes containing modern synthetic resins of phenol character (4-hour varnish) are more durable than those made with glycerin esters of rosin. It would seem, therefore, that requirements should include these newer type varnishes, and their use will be followed by even greater durability than is obtained at the present time. A competitive durability test might be an added requirement to specifications.

The air brush has come into wide use in the finishing of aircraft. Much greater speed is made through the use of this device than with the hand brush. Hand brushes are generally preferred, however, for oil or varnish coatings and air brushes for lacquer coatings. In doping wing surfaces, it is believed advisable to apply the first two coats by hand brush. Better penetration and less lint on the surface may result by this method. For all subsequent coats, it is probable that the spray brush is well adapted and will save much time. In this connection, it is believed that airplane cloth could profitably be produced in a form that would show less lint than is apparent at the present time when the cloth is doped. The presence of the nap which is raised by the first coats of dope is objectionable, and difficult at times to sand off without affecting the fabric and forming little channels where moisture may ultimately be admitted. It is also believed that within a comparatively short period of time, new types of airplane cloth will be available in pre-doped form. The author has during the past two years experimented in the development of pre-doped cloth which, when stretched over a wing surface, will become taut through the application of only two coats of dope rather than six coats which are often used at the present time.

Where the longerons come in contact with the fabric, they should first be protected with a dope-proof paint or with tire tape or aluminum foil. The aluminum foil probably gives the best insurance against the admission of moisture to the longerons and at the same time protects the fabric from rotting which might otherwise occur. While 0.005-in. aluminum foil has been used for this purpose, with an adhesive, the author has found that paper-backed foil is more practical, as better adherence is obtained.

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[1] C. L. Came, "Durability Tests of Spar Varnish," *Journal of Research*, U. S. Bureau of Standards, February, 1930.

[For Discussion on Protective Coatings, see page 184.—ED.]

APPLICATIONS OF STAMPINGS, FORGINGS AND CASTINGS IN AIRCRAFT CONSTRUCTION

By H. G. Runde[1]

Synopsis

Aircraft construction has developed an advanced type of design peculiar to itself because of the unusual importance of lightness and strength. Consisting of a primary structure, the fuselage, to which the several other units are attached, there are required numerous parts to accomplish these attachments. Because of the limited production of aircraft and particularly in the case of experimental models, these parts have been machined from solid stock or fabricated from bar, sheet and tubing. With increased production, however, this method becomes prohibitively expensive and the more economical processes of casting, stamping and forging are employed. In general, the built-up or machined fitting is used for very small production; castings, with due regard for their lower physical properties, in designs of intricate shape and for production of an intermediate quantity; stampings and forgings for mass production and where the improved physical properties, increased soundness and greater reliability are required in spite of the higher cost.

No definite rule can be laid down to indicate at what quantity of pieces the choice changes and with no fixed production the designer is confronted with a perplexing problem. He must construct his experimental machine with which to create a production demand by demonstrated merit, without prohibitive expense, and yet keep in mind the application of production refinements without complete redesign, when the demand arises.

The use of stampings, forgings and castings has increased in the aircraft industry in the last few years and as production grows the application of these methods of fabrication will increase correspondingly. There are shown fifteen illustrations of typical aircraft parts.

Aircraft construction has developed an advanced type of design peculiar to itself because of the unusual importance of lightness and strength. The primary structure is the fuselage to which it may be considered the various other units are attached, namely, the wings with ailerons, tail surfaces, tail skid or wheel, landing gear and engine mount. These were originally of wood but are now almost entirely of metal. There are required a great number of attachments, both fixed and movable, which are variously referred to as brackets, sockets, bearings, clamps, horns, hinges, plates, yokes, etc., but which fall under the generic classification of fittings.

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[1] Chief of Materials Department, Curtiss Aeroplane and Motor Co., Garden City, L. I., N. Y.

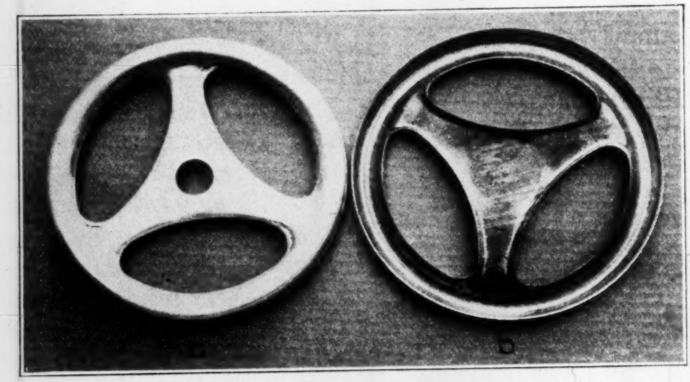

FIG. 1.—Duralumin Sheet Stampings.

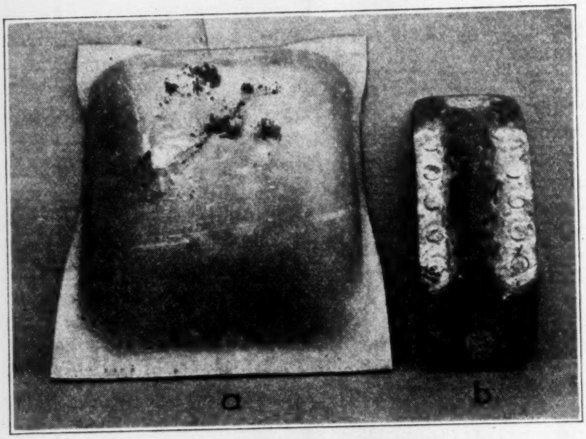

FIG. 2.—Components of a Tail Skid Shoe.

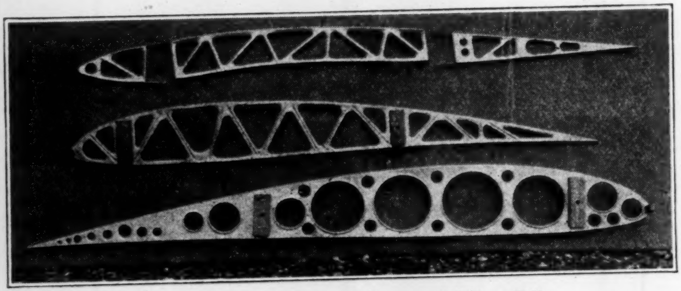

FIG. 3.—Showing Three Types of Wing Ribs.

When the quantity of these parts was small because of the limited production of aircraft, particularly in the case of experimental machines, the industry was dependent upon machining these fittings from solid stock or upon fabricating them from sheet, tube and bar stock joined together by various methods such as riveting, welding, brazing and soldering. There was no easy or economical substitute for this method of construction which had obvious limitations, particularly when high-strength materials were necessary. As production increased, however, these methods of construction became prohibitive due to expense, and the production processes of casting and particularly of stamping and forging began to be employed. To illustrate: A built-up fitting may be assumed to cost $10 per piece. If ten pieces are required, a casting pattern at $30 and molding and casting costs at $2 per piece would make a total of $5 per piece in this quantity. For one hundred pieces a forging die at $200 might further reduce the price per piece to $2.50 including material and labor and in addition produce parts of improved physical properties.

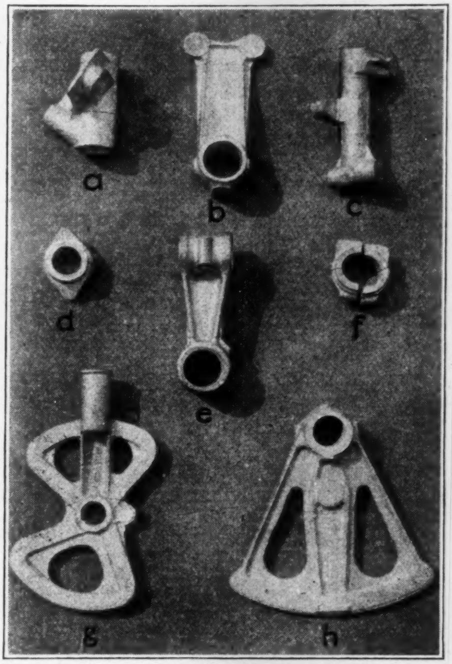

FIG. 4.—Aluminum-Alloy Castings Used in Control Systems.

Unfortunately no definite rule can be laid down to indicate for what quantity of pieces the choice between stamping, casting or forging changes. This is influenced by the cost of patterns or dies, which in turn is dependent upon the simplicity of design of the part. Cost, however, is not the only factor which governs the choice of construction to be adopted. The use for which a part is intended in some cases warrants the use of a forging in spite of its expense because of the better physical properties of the material which can be developed or because of the advantages obtained by having an integral construction rather than a built-up structure which may be unsatisfactory in regard to reliability, rigidity, strength, or weight. This is particularly true of those forgings which can obtain the full advantage of the excellent physical properties developed in wrought materials through heat treatment. In contrast to these are castings in which lower strengths are developed and in which ample provision for possible flaws must be made. Parts of intricate shape are, however, frequently produced as castings because of economy and convenience. In short, the built-up or hogged-out fittings are necessarily employed for cheapness in experimental or very small production orders; castings may be used with due regard for lower physical properties in designs of intricate shapes and for all shapes in production orders of an intermediate quantity; stampings and forgings are generally used for mass production or as a substitute for castings or built-up fittings because of improved physical properties, increased soundness, greater accuracy and lower cost.

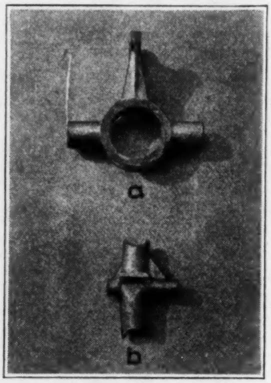

FIG. 5.—Manganese-Bronze Castings of Control Stick Universal and Landing Gear Bearings.

There is a certain class of parts generally known as "standard parts" which may be used in some quantity in a single type of plane or in several types of planes. There is another group of parts which, while of wide utility to a single manufacturer, cannot be called standard with the industry, which are used in sufficient quantity over a period of time to make it of advantage to use the more economical production forms of construction. In the last few years the aircraft industry has increased its use of stampings, castings and forgings to a very great extent and with a demand for increased production of airplanes, there will come a still wider use of these methods of fabrication. In the transition period in design from experimental to production quotas and with uncertain markets, a designer has a per-

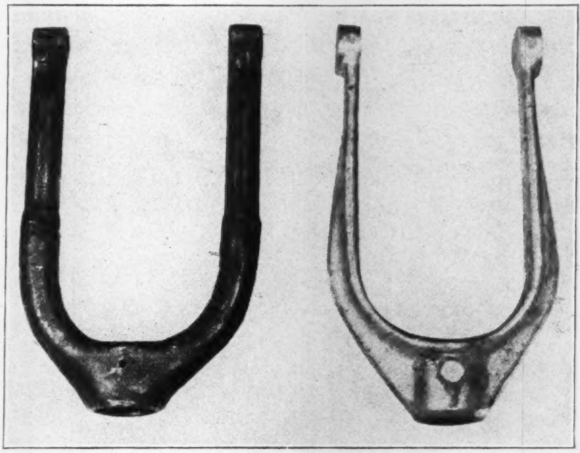

FIG. 6.—Welded Tail Skid Fork and Cast Aluminum-Alloy Tail Skid Fork.

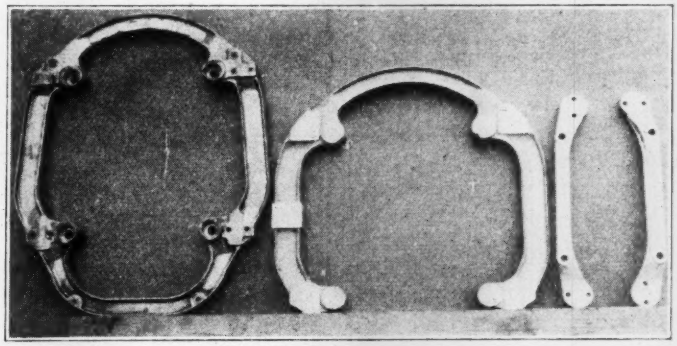

FIG. 7.—Showing Evolution of an Air-Cooled Engine Mount.

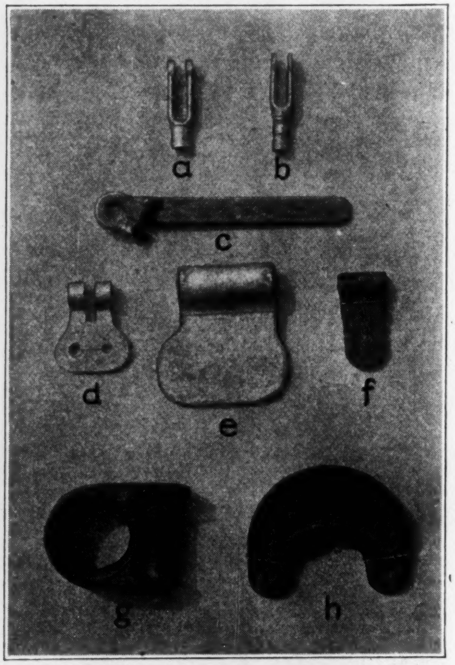

FIG. 8.—Showing a Number of Standard Parts Being Adaptable to Forging.

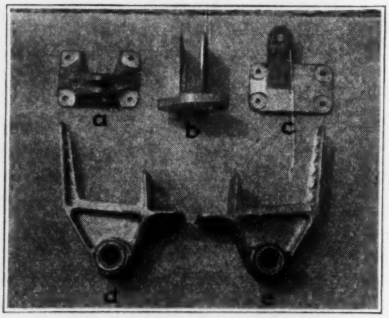

FIG. 9.—Fittings Machined from Forged Blocks.

plexing problem to face in his choice of production methods. So far he has usually constructed the first machine according to the quickest and most economical means, leaving production refinements of design and manufacture until such time as a production demand was created by demonstrated merit. The situation results that the experimental plane must not be prohibitive in expense and yet those types of construction which will be cheaper in quantity production must be kept in mind so that increased production may be possible without complete redesign. It is unfortunate in this respect that progress has been so rapid that no model remains in existence long enough to permit proper study and refinement of design and production of its individual fittings. The result is a continual compromise. In the past, cost has not been so important as it has been in other industries, the effort having been to develop the best flying machine by any means available. The cost of producing that machine is now being recognized and is playing a part of ever increasing importance.

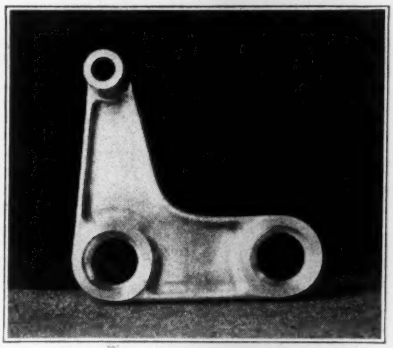

FIG. 10.—Aileron Control Lever.

In Fig. 1, *a* is composed of two of the duralumin sheet stampings, *b*, welded together. This is a cheaper and lighter construction than used in the aluminum alloy casting which it replaced. In Fig. 2 are the components of an unusual tail skid shoe, a $\frac{1}{4}$-in. dural plate stamping, *a*, to which is attached the cast manganese steel shoe, *b*.

Typical parts for which stampings may be effectively used in addition to fittings are radiator shells for water-cooled motors, streamline shapes for exposed struts and similar parts that need to be streamlined, fuel and oil tanks, wheels, brake and shock absorber units. A most fertile field lies in the many ribs of all types, whether for wings, tail surfaces, floor or walk bracing. Figure 3 shows three types of wing ribs. Rib *a* is constructed in three parts to facilitate replacement of damaged members. For the production of rib *b* an elaborate and costly die was built which completed the rib in one piece and in one operation. Such an expensive die is warranted only by a large production. Rib *c* may be readily and cheaply produced in small quantities by forming the flanged holes with cheap wooden or lead dies.

Castings have found, perhaps, a wider use in the past than have forgings because of their cheapness in limited numbers and the convenience with which difficult shapes may be formed. There is a predominance of the aluminum alloys because they offer a satisfactory strength-weight ratio combined with good casting qualities, good machineability and comparative freedom from flaws. Figure 4 illustrates a representative group of aluminum-alloy castings variously used in control systems. This includes a support for elevator cable pulley and stabilizer adjustment, *a*; a control stick aileron horn, *b*; an aileron control bellcrank, *c*; bearing for stabilizer control shaft, *d*; control stick rear bearing, *e*; aileron hinge bearing, *f*; control

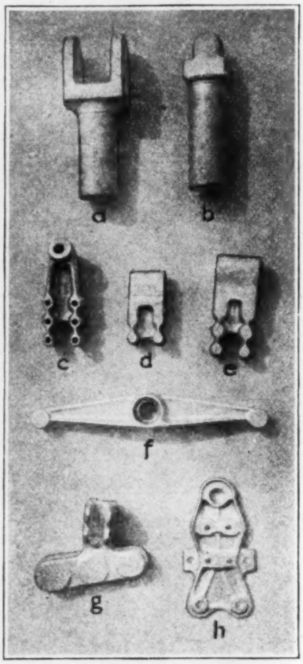

FIG. 11.—Showing a Variety of Forged Fittings.

stick aileron sector, *g*; and stabilizer adjusting control quadrant, *h*. In Fig. 5 there are two manganese-bronze castings, a control stick universal bearing, *a*, and the two parts, *b*, of a landing gear bearing. Figure 6 illustrates a cast aluminum-alloy tail fork and the built-up type which it replaced. The cast fork represents a decrease in weight of 40 per cent and in cost of about 25 per cent. Figure 7 shows the evolution of an air-cooled engine mount. The original ring casting was soon replaced by the horseshoe, also an aluminum-alloy casting of the heat-treated type. This was in turn superseded by the two aluminum-alloy forgings shown at the right.

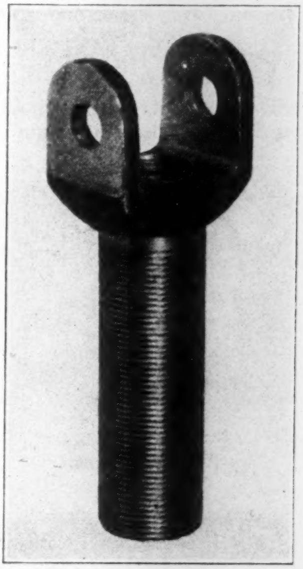

FIG. 12.—Strut Adjustment Forging.

In Fig. 8 are illustrated a number of those standard parts of such general utility as to have been early adaptable to forging. The clevises require no explanation. Parts *a*, *b*, *d* and *f* are of steel and part *e* is of aluminum alloy. The aluminum-alloy control shaft lever, *e*, has replaced a manganese-bronze casting at one-half the cost and 40 per cent of the weight. Part *g* is an engine bed tie clamp used as a support for water-cooled engines and part *h* is a drag-wire plate. Both are of steel. To obtain the advantages of a forging for anticipated production the fittings of Figs. 9 and 10 were machined from forged blocks for the first plane. In Fig. 9, *a* and *c* are cabane strut fittings, *b* serves as a bracket for the attachment of bracing supporting

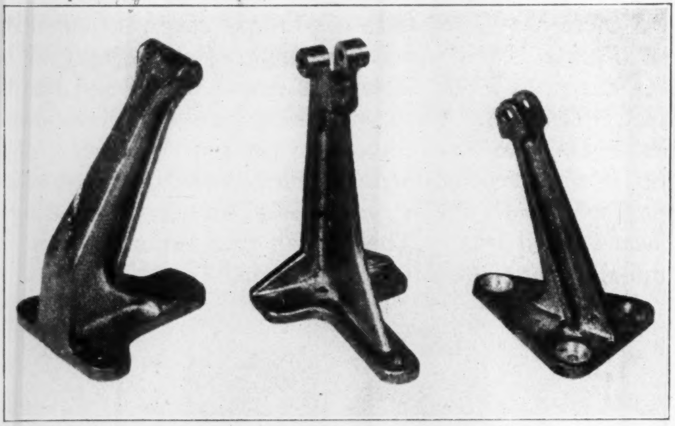

FIG. 13.—Three Types of Cast Aluminum Aileron Hinges.

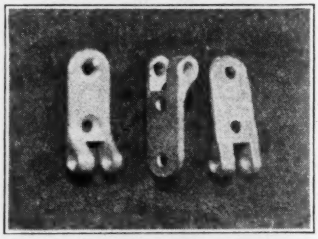

FIG. 14.—Drop Forgings of Aileron Hinges.

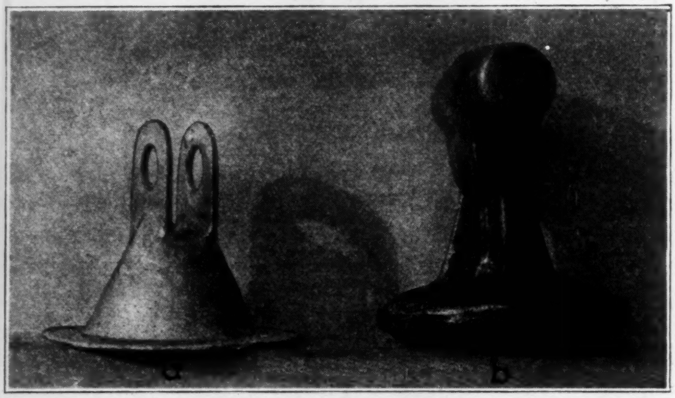

FIG. 15.—Showing Forging and Welded Stamping Which It Replaced.

the cover of a metal covered compartment. Parts *d* and *e* are fuselage rear wing beam hinge fittings. Figure 10 is an aileron control lever. In Fig. 11 are illustrated a variety of forged fittings in aluminum alloy. Parts *a* and *b* are fuselage wing hinge fittings of a simpler construction than those illustrated by *d* of Fig. 9. Parts *c*, *d* and *e* are strut ends adapted for riveting into the ends of streamline shaped struts. Fitting *c* has been drilled for the rivets. Fitting *f* is a control horn; *g* is a fitting which serves as the joint for attachment of oleo landing gear and wing brace struts. Part *h* is a wing hinge fitting. The complete hinge consists of two of the forgings shown bolted to the wing beam, one on either side. Figure 12 is a strut adjustment forging of steel. It represents a saving of 30 per cent in both cost and weight over a complicated built-up structure which it replaces.

An example of the production in varied forms and materials of construction of parts performing the same function is demonstrated in the aileron hinges of Figs. 13, 14 and 15. Figure 13 show types of cast aluminum alloy and Fig. 14 a drop forging. Figure 15 shows a forging, *b*, which is replacing the welded stamping construction, *a*.

[For Discussion on Stampings, Forgings and Castings, see page 192.—ED.]

MATERIALS OF CONSTRUCTION IN AIRCRAFT ENGINES

By R. R. Moore[1]

Synopsis

This paper covers briefly the various steels, bronzes and brasses and light alloys that are most commonly used in the construction of aircraft engines.

Physical properties and chemical analyses of the alloys are given. The applications of the various alloys together with the reasons for the specific uses of each are explained in detail.

The two outstanding demands of the aircraft engine from the construction standpoint are lightness and reliability. These qualities oppose rather than assist each other and, therefore, intensify the importance of the type and quality of the materials used.

The metals employed in the construction of aircraft engines represent such a great variety of types and forms that they cover practically the entire field of structural alloys. These metals vary in weight and strength from the light aluminum and magnesium alloys to the tough strong steels and heavy bronzes. They will be found to be applied in all commercial forms such as forgings, castings, sheet, tube, bar, wire and in various specialties of each of these forms.

The total weight of a radial air-cooled engine is made up of about 45 per cent aluminum alloys, about 3 per cent bronze and the remaining 52 per cent steel. There is a negligible amount in rubber, felt, vellum, cork, etc. The relatively large percentage of light alloys used in aircraft engines accounts of course for their light weight. The purpose of using light alloys is not only to cut down the dead weight of engines, but also to reduce the weight of reciprocating parts.

Light Non-Ferrous Metals

The aluminum-base alloys are particularly well adapted to aircraft construction because of their lightness and thermal characteristics. Without the light alloys aircraft and aircraft engines would not have reached their present stage of development. If all the aluminum alloys used in an air-cooled aviation engine were replaced by steel, cast iron, or bronze, the weight of the engine would be about doubled.

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The more important parts made from the alloys of aluminum or magnesium are the crankcase, pistons, cylinder heads, pump bodies, diffuser disk, supercharger impeller, intake pipes, housings, covers and cowling. In Table I is given a list of alloys that have been used and their physical properties. The practice among engine manufacturers is not uniform, there being considerable difference as to the alloy used and the form of manufacture.

TABLE I.—LIGHT ALLOYS USED IN AIRCRAFT ENGINES.

Alloy	Chemical Composition								Alcoa Number	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Specific Gravity	Form
	Aluminum, per cent	Copper, per cent	Silicon, per cent	Iron, per cent	Zinc, per cent	Magnesium, per cent	Nickel, per cent	Manganese, per cent						
A	92	8	...	....	...	...	....	....	...	11 000	18 000	1.0	2.86	Sand Casting
B	88	12	...	....	...	...	....	....	...	13 000	20 000	1.0	2.95	Sand Casting
C	94.65	4.5	0.65 to1.10	0.85 max.	...	...	....	....	195	18 000	25 000 to 35 000	6 to 11	2.77	Sand Casting—Heat Treated[a]
D	85.50	2.75	...	1.50	10.25	...	.		..	12 000	25 000 to 34 000	3 to 6	....	Sand Casting
E	92.5	4.0	...	....	...	1.50	2.0	. .	...	27 000	28 000 to 38 000	1.0	....	Sand Casting—Heat Treated[b]
F	88.5	10.0	...	1.25	....	0.25		. .	122	20 000	35 000 to 40 000	1.0	....	Sand Casting
G	93.0	4.0	3.0	....	...	...	. .	. .	...	....	17 000	1.5	....	Sand Casting
H	94.0	...	6.0	....	...	..	....	....	...	7 000	19 000	3 to 7	....	Sand Casting
I	7.0	...	...	....	...	92.6	....	0.4	...	9 500	32 000	8	1.74	Sand Casting—Heat Treated[c]
K	87.0	...	13.0	....	...	...	....	....	...	....	28 000 to 33 000	1 to 4	....	Die Casting and Permanent Mold
L	98.5	...	0.90	....	...	0.60	....	....	51S	30 000 to 40 000	45 000 to 50 000	10 to 18	2.69	Forging—Heat Treated[d]
M	93.9	4.5	0.80	....	...	...	....	0.80	25S	30 000 to 40 000	55 000 to 63 000	16 to 25	2.79	Forging—Heat Treated[e]
N	94.8	4.0	...	....	...	0.50	....	0.70	17S	30 000 to 40 000	55 000 to 63 000	18 to 25	2.74	Forging—Heat Treated[f]

[a] Heat to 950 to 975° F. and soak, quench in water, hold at 212° F. for one hour.
[b] Heat to 935 to 975° F., quench in water, hold at 450° F. for one hour.
[c] Heat to 790° F., quench in water, hold at 250° F. for three hours.
[d] Heat to 950 to 985° F., quench in water, hold at 320° F. for eighteen hours.
[e] Heat to 950 to 985° F., quench in water, hold at 290° F. for eight to fifteen hours.
[f] Heat to 925 to 960° F., quench in water, hold at 212° F. for one hour.

Crankcases are made from any of the alloys A, B, C or D shown in Table I. The actual alloy used depends upon the type of engine and the part of the crankcase to which it is applied. The highest tensile strength and elongation is obtained from alloy C when heat treated. This alloy is, therefore, used on the most highly stressed parts. Alloy D has been used on small four-cylinder engines. This, however, is not general practice as objections to its use are found in the low proportional limit and its susceptibility to salt water corrosion.

In some radial engines the main crankcase section is a forging made from alloy L which is then heat treated. This, of course, gives a much stronger part. However, the modulus of elasticity of the forged and heat-treated alloy L and the cast alloy C are practically the same. This means that under the same stresses below the elastic limit the deformation is practically the same in each case. For this reason any gain in weight obtained by decreasing the wall thickness of the forged crankcase is done at the expense of stiffness. The forged crankcase, however, has the advantage of a higher yield point which means that higher stresses can be endured without assuming permanent set as might occur in the case of occasional over stress. Furthermore, the forging has greater ductility which will permit more distortion before cracks and ruptures are started. Unless forgings are used in a great quantity they are not cheaper than castings because of the high die costs which add considerably to the price of each forging when only a few are made. A disadvantage of the forged crankcase is the limitations of the designer to place bosses, passage ways, grooves, etc., integral with the casting. A crankcase must be designed specifically for a forging or for a casting. One type of manufacture cannot be converted to the other without radical changes in design.

Rear crankcase sections of radial engines have also been made from the magnesium-base alloy I which is considerably lighter than any of the aluminum alloys and has excellent physical properties. Due to the difficulty of handling magnesium in the foundry and the susceptibility of this alloy to corrosion, magnesium alloys have not developed very rapidly until recently. Improved methods of handling have been devised which greatly facilitate the casting of magnesium. The susceptibility of magnesium alloys to corrosion has been greatly reduced by the use of magnesium of higher purity and the addition of special elements to the alloy. In designing parts to be made from magnesium alloys it should be remembered that the modulus of elasticity is only about 6,250,000 lb. per sq. in. as compared to a value of 10,250,000 lb. per sq. in. for the aluminum alloys. This means that the magnesium alloy is subjected to greater deformation under load. Experimentally, various other parts such as crankcase sections, supercharger housings, oil pump sumps have been made of magnesium alloys.

Cylinder heads on air-cooled engines are made of aluminum-alloy castings on all large engines and have been made from cast iron on a few small engines below 100 h.p. Aluminum alloys are used for heads, not only to reduce the dead weight of the engine but also to provide sufficient cooling for the combustion chamber. The thermal conductivity of aluminum alloys is about three times that of cast iron. This high thermal conductivity makes aluminum heads less subject to hot spots, local weakness and cracks. The two alloys most used are alloys E and F. The primary reason for their use is that they have a greater strength at high temperature than most other aluminum alloys. One British manufacturer makes the head from alloy E forged. This requires much difficult and expensive machining and would not be welcomed by American manufacturers.

Pistons are made from alloys E, F and A in sand castings and from alloy K in permanent-mold castings. The light alloys are used for pistons, not only to decrease the dead weight but also to decrease the inertia forces of the reciprocating pistons. As in the case of cylinder heads, the advantages of high thermal conductivity of aluminum alloys are less susceptibility to hot spots, local weakness and cracks. One disadvantage of the aluminum alloys for pistons is their high coefficient of expansion which requires greater clearances between the piston and the cylinder wall. The alloy K which is high in silicon has certain advantages over alloys E, F and A in that it is lighter and has a lower coefficient of expansion than these alloys. A decided disadvantage of this alloy is that it is extremely difficult to machine.

Intake manifolds and other thin-walled castings offer some casting difficulties and are usually made from alloy G or H in order to eliminate foundry losses due to misruns. These silicon alloys show a low shrinkage which facilitates the production of complicated castings. They have good tensile strength and elongation and are dense and pressure tight, but show a low yield point and are somewhat difficult to machine.

When such parts as covers or lids are used in multiple on engines, so that they run to large quantities, die castings are desirable. The practical advantage of die castings is that they can be finished very closely to dimensions and produce castings with very smooth surfaces; practically no machining is required; holes can be placed with great accuracy; when used in quantities, die castings are cheaper than sand castings. There is no doubt that die castings will find an increasingly large application for unstressed parts of aircraft engines. Apparently a wide field for this type of casting is in aircraft accessories such as the carburetor, certain types of which have become more or less standard on several types of engines.

On small engines, rating 100 h.p. or less, connecting rods are sometimes made from aluminum alloy forgings. The alloys generally used are alloys M or N which are heat treated to produce the physical properties shown in Table I. It has not been found practical to employ aluminum-alloy connecting rods on large engines.

Intake pipes on radial engines are made from aluminum tubing. Cowling is made from aluminum sheet. These parts are unimportant structurally; the only precaution to be observed is that the sheets or tubes are of the proper temper to permit forming without rupture, as required from the design of these parts.

BRASS AND BRONZE

Brass and bronze make up a very small portion by weight of the metals used in aircraft engine construction. They are heavy alloys and for that reason are avoided when possible. At present, however, certain special parts such as bearings and certain gears are best made of bronze. The uses of brass and bronze for structural parts and miscellaneous fittings are due to special features of these alloys. In Table II is given a list of alloys and their chemical compositions and physical properties.

TABLE II.—BRASS AND BRONZE.

Alloy	Name	Chemical Composition										Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	S.A.E. Designation
		Copper, per cent	Tin, per cent	Zinc, per cent	Lead, per cent	Phosphorus, per cent	Nickel, per cent	Manganese, per cent	Iron, per cent	Aluminum, per cent	Silicon, per cent				
No. 1	Cast Bronze	88	10	2	...	...	...	...	...	...	...	18 000 to 20 000	30 000 to 45 000	15 to 25	No. 62
No. 2	Phosphor Bronze	89	11	...	...	0.25	...	...	...	...	...	20 000 to 23 000	30 000 to 40 000	10 to 15	No. 65
No. 3	Bearing Bronze	80	10	...	10	0.25	...	...	...	...	...	14 000	26 000	8	No. 64
No. 4	High Lead Bronze	74	5	...	21	...	...	...	...	...	...	12 000	20 000	8	....
No. 5	Nickel Bronze	83.5	10	...	3	...	3.5	...	...	...	...	25 000	38 000 to 47 000	7 to 12	....
No. 6	Red Brass	88	5	5	5	...	...	...	...	...	...	15 000 to 18 000	26 000 to 32 000	15 to 20	No. 40
No. 7	Yellow Brass	63	...	34	3	...	...	...	...	...	...	12 000	25 000	20	No. 41
No. 8	Manganese Bronze	60	...	40	...	...	...	...	...	...	...	30 000	60 000	15	No. 43
No. 9	Super Manganese Bronze	69	...	20	...	...	...	2	2.5	6.5	...	50 000 to 57 000	101 000 to 110 000	5 to 10	....
No. 10	Aluminum Bronze	89	...	...	...	...	...	...	1.0	10	...	22 000 to 26 000	60 000 to 75 000	15 to 25	....
No. 11	Special Aluminum Bronze	79	...	...	...	...	5.0	...	5.0	11	...	[a]	[a]	[a]	[a]
No. 12	Free Cutting Brass Rod	62	...	35.5	2.5	...	...	...	...	...	...	....	....	...	No. 72
No. 13	Extruded Aluminum Bronze	89	...	...	...	...	...	...	1.0	10	...	37 000	75 000	20	....
No. 14	Everdur	95.5	...	...	...	...	...	1	...	...	3.5	....	....	...	....

[a] Heat treated to a Brinell hardness of 200.

A large number of bearing bushings are made from alloys Nos. 1 and 3. An excellent bearing capable of withstanding considerable loading and offering good bearing qualities is made from alloy No. 5. For bearings which have to operate under poor lubricating conditions the high-lead bronze alloy No. 4 is good. For spiral or worm gears phosphor bronze alloy No. 2 or the nickel bearing bronze alloy No. 5 have been very successful. The characteristics of alloys Nos. 2 and 5 are greatly improved by chilling which refines the grain and increases the hardness considerably.

For parts of complicated shape which are, therefore, required to be cast, either of the alloys Nos. 6, 7, 8, 9 or 10 are used, depending upon the requirements. The red and yellow brass alloys Nos. 6 and 7 fulfill the requirements for the cheaper brass of low strength and are easily machined. These alloys are used for unimportant parts such as plugs, fittings, caps, etc. When a higher strength alloy is required the magnesium bronze alloy No. 8 or aluminum bronze alloy No. 10 are used. The aluminum bronze has a better resistance to impact and excellent fatigue resisting properties. It has been used successfully on spiral and worm gears. Alloy No. 11 is an aluminum bronze of higher iron content and added nickel and it responds very well to heat treatment. When a very high strength bronze is desired alloy No. 9 is used. This alloy also responds to heat treatment and will harden to a Brinell hardness of about 200 or 225.

Alloy No. 12 is used for parts of simple design that can be made on the screw machine and do not require any great strength. When greater strength is required an aluminum bronze alloy No. 13 or the copper-silico-manganese alloy No. 14 can be used.

STEELS

The selection of the proper steel to be used in various parts of an aircraft engine involves more than the mere writing of an S.A.E. number on the drawing. Behind the selection of a steel for a particular purpose there are a number of considerations to be taken into account. These not only relate to the performance of the steel but also to the methods of preparation which are necessary to put it into the proper condition to perform the functions demanded of it. The performance of steels is generally based on such properties as elastic limit, strength, hardness, ductility, fatigue, wearing quality, etc. However, these properties are only a few of those that contribute to the successful application of metals. Due consideration must also be given to such factors as uniformity, depth of hardening, tendency to warp, hardening range, forgeability, machineability, etc. All of these properties are inherent in the alloy and contribute to its success or failure in performing the functions for which it is intended.

A common method of selecting steels for certain parts has been to adopt the same steel as used in a similar part in some other engine.

The defect in this system is that no two engines are exactly alike and a steel that proves successful in one engine may not prove successful in another of apparently similar design, because the service conditions to which the part is subjected are not as nearly alike as is commonly supposed. Two very good examples of this are valves and valve springs. Another method of selecting steels is on the basis of price. This is particularly bad practice in aircraft work. There is very little economy in using cheap steels, because in the final analysis

Table III.—Steels Used in Aircraft Engines.

Steel	Designation	Chemical Composition								
		Carbon, per cent	Manganese, per cent	Nickel, per cent	Chromium, per cent	Vanadium, per cent	Molybdenum, per cent	Tungsten, per cent	Cobalt, per cent	Silicon, per cent
Bars or Forgings										
Low Carbon	S.A.E. No. 1010	0.10	....	....	....	....	....	....	....	....
Mild Carbon	S.A.E. No. 1025	0.25	0.65	....	....	....	....	....	....	....
Medium Carbon	S.A.E. No. 1050	0.50	0.65	....	....	....	....	....	....	....
High Carbon	S.A.E. No. 1095	0.95	0.40	....	....	....	....	....	....	....
Nickel	S.A.E. No. 2330	0.30	0.65	3.50	....	....	....	....	....	....
Nickel	S.A.E. No. 2512	0.17 max.	0.45	5.0	....	....	....	....	....	....
Nickel Chromium	S.A.E. No. 3140	0.40	0.65	1.25	0.60	....	....	....	....	....
Nickel Chromium	S.A.E. No. 3115	0.15	0.45	1.25	0.60	....	....	....	....	....
Nickel Chromium	P	0.45	0.65	1.75	0.75	....	....	....	....	....
Nickel Chromium	Q	0.40	0.75	1.50	0.80	....	....	....	....	....
Nickel Chromium	S.A.E. No. 3250	0.50	0.45	1.75	1.10	....	....	....	....	....
Nickel Chromium	S.A.E. No. 3312	0.17 max.	0.45	3.50	1.50	....	....	....	....	....
Nickel Chromium	S.A.E. No. 3335	0.35	0.45	3.50	1.50	....	....	....	....	....
Chromium	S.A.E. No. 52100	1.00	0.35	....	1.35	....	....	....	....	....
Chromium Molybdenum	S.A.E. No. 4150	0.50	0.55	....	0.95	....	0.20	....	....	....
Chromium Vanadium	S.A.E. No. 6120	0.20	0.65	....	0.95	0.18	....	....	....	....
Chromium Vanadium	S.A.E. No. 6135	0.35	0.65	....	0.95	0.18	....	....	....	....
Chromium Vanadium	S.A.E. No. 6150	0.50	0.65	....	0.95	0.18	....	....	....	....
Chromium Vanadium	S.A.E. No. 6195	0.95	0.35	....	0.95	0.18	....	....	....	....
Tungsten	S.A.E. No. 71660	0.60	0.30 max.	....	3.50	....	....	16.50	....	....
Cobalt Chrome	R	1.30	0.40 max.	....	13.0	....	0.70	....	3.0	....
High Nickel Chromium	S	0.35	0.65 max.	8.0	13.0	....	....	....	....	2.5
Chromium Silicon	T	0.45	0.50	....	8.0	....	....	....	....	3.25
Sheet Steel										
Low Carbon	S.A.E. No. 1010	0.10	0.45	....	....	....	....	....	....	....
Mild Carbon	S.A.E. No. 1025	0.25	0.65	....	....	....	....	....	....	....
High Carbon	S.A.E. No. 1095	0.95	0.40	....	....	....	....	....	....	....
Chromium Vanadium	S.A.E. No. 6130	0.30	0.65	....	0.95	0.18	....	....	....	....
Chromium Molybdenum	S.A.E. No. X4130	0.30	0.55	....	0.95	....	0.20	....	....	....
Tube										
Mild Carbon	S.A.E. No. 1025	0.25	0.65	....	....	....	....	....	....	....
Chromium Molybdenum	S.A.E. No. X4130	0.30	0.55	....	0.95	....	0.20	....	....	....
Wire										
Carbon Steel Spring Wire	V	0.70 to 1.00	0.45	....	....	....	....	....	....	....
Music Wire	S.A.E. No. 1095	0.95	0.30	....	....	....	....	....	....	....
Chromium Vanadium	S.A.E. No. 6150	0.50	0.65	....	0.95	0.18	....	....	....	....

such practices often result in considerably greater expense, due to losses during heat treatment and in scrapping parts made from defective material to say nothing of the enormous losses incurred by failures in service.

The steels make up the major part by weight of the engine. A general survey of the various steels used in aircraft engine construction will show that most of the standard S.A.E. steels have been applied in some form or other. Table III shows the general types of steels more commonly employed in aircraft engine construction. This list does not attempt to cover the entire field as many variations of the alloys given are used, particularly in reference to the carbon content of the different alloys.

In the plain carbon class of steels the grades of low carbon, mild carbon, medium carbon and high carbon find some application. In a few cases the low-carbon steels are carburized and used for such parts as cam shafts, tappet guides and rollers. The mild carbon steels are generally employed for miscellaneous parts such as pins, dowels, plugs, caps, etc., which do not require any particular strength. The medium-carbon steel is quite generally adopted for cylinder sleeves in the air-cooled type engines. It is also used for parts which require a slightly greater hardness than is obtained with the mild-carbon steel. The high-carbon steels find a limited application for hardened pins. Drill rod, which is high in carbon but somewhat variable in content, finds considerable use as it has a special value due to the fact that it can be obtained cold drawn to size within very close tolerances.

The nickel steels similar to S.A.E. No. 2330 or with somewhat higher carbon content find considerable use in bar form for such parts as bolts, studs, nuts, small shafts and in the form of forgings for rocker arms and small connecting rods which do not require great hardness. This steel has an advantage for such small forgings because it forges well and is not readily overheated. It is not generally used for large forgings because it lacks penetration in hardening. The high-nickel steel known as S.A.E. No. 2512 is a case-hardening steel and is rated as one of the best for such applications as gears and highly stressed parts which require a very tough core and a hard surface. The advantage of this steel is that it gives a very tough core and hard case with good grain refinement of both after a single quench from about 1425° F. Because of the comparatively low quenching temperature it is often used on complicated parts that are prone to warp during hardening.

The nickel-chromium steels in general are very widely used in aircraft construction. The alloys shown as S.A.E. Nos. 3140 and 3335 represent some of the most widely used of this class of steels. For forgings such as crankshafts, connecting rods, oil-hardened gears and other highly stressed parts, the alloys shown as P, Q and S.A.E. Nos. 3140, 3250 and 3335 are probably the most common. The selection of any particular one of these steels depends upon the size, form, and function of the part. Alloys Nos. 3140, 3250 and 3335, which are standard S.A.E. steels, are very broadly used. Alloys P and Q which are special steels not within any S.A.E. classification are used for large crankshafts where it is difficult to get complete hardening throughout the section.

The chromium-nickel case-hardening steels S.A.E. Nos. 3115 and 3312 are widely used. Alloy S.A.E. No. 3115 is generally used for parts that require a somewhat greater core strength than can be obtained with the plain carbon carburizing steel S.A.E. No. 1010 and which require a higher quality of steel. The applications of this steel are gears and shafts which do not require as tough a core as is obtained with the 5-per-cent nickel case-hardening steel S.A.E. No. 2512. The steel S.A.E. No. 3315 is often used as a substitute for the high-nickel steel S.A.E. No. 2512 as it also develops a very tough core. There is not much to choose between these two steels and they will be found used interchangeably. The chromium-vanadium steel S.A.E. No. 6120 is also used alternately with the S.A.E. steels Nos. 3315 and 2512. It gives a very high case hardness and fine grain structure.

For parts made from bar stock such as minor gears, piston pins, knuckle pins, bolts and studs the chromium-nickel steels S.A.E. Nos. 3140, 3250 and 3335 or variations of these steels are generally used. These steels can be hardened to a Rockwell hardness of about 54 without producing brittleness and the steel is still in a satisfactory structural condition to resist repeated stresses. Substitutes for these steels are sometimes made with the chromium-molybdenum steel S.A.E. No. 4150 and the chromium-vanadium steels S.A.E. Nos. 6135 and 6150. The chromium-molybdenum and chromium-vanadium steels can be heat treated to produce practially the same physical properties as the chromium-nickel steels.

. For parts that require extreme hardness without resorting to carburizing, such as ball and socket fittings for push rods and for hardened pins the high-carbon chromium steel S.A.E. No. 52,100 and the high carbon chromium vanadium steel S.A.E. No. 6195 are of particular value. These steels will readily harden to a

Rockwell hardness of 60 without producing a brittle condition. They also show a particularly good wearing surface.

The special steels such as the high-speed tungsten steel S.A.E. No. 71660, the cobalt-chromium steel R, the high-nickel chromium steel S and chromium-silicon steel T are used extensively for valves. There is a wide divergence of opinion in regard to which particular steel to use in a specific installation. The selection of the proper alloy depends upon the operating conditions and the design of the valve and can only be satisfactorily made after a careful study of the characteristics of each. The tungsten and the cobalt-chromium steels are characterized by their ability to retain extreme hardness at high temperatures and thus resist wear on both the valve stem and valve tip. The same is true of the chromium-silicon steel T but to a somewhat lesser extent. These steels also show less scaling and warping at operating temperatures than ordinary structural steels. The particular value of the high nickel-chromium steel S lies in its resistance to corrosion and to the fact that it is very tough, having an Izod value of about 100. This alloy is an austenitic steel and cannot be hardened. It is comparatively soft and, therefore, much less resistant to wear. Another drawback in the use of this steel is the great difficulty in machining it.

There are several minor parts and accessories to the engine which require sheet or strip steel for stamping and forming operations. These parts are generally made from the low-carbon steel S.A.E. No. 1010 or the mild carbon sheet steel S.A.E. No. 1025, depending upon the severity of the forming operation. Occasionally washers or plates of extreme hardness are desired. They are best made from sheet steel. In this case the high-carbon steel S.A.E. No. 1095 is satisfactory. The steel is obtained in the annealed condition and heat treated after finishing to produce the required hardness. This steel may also be used for flat springs. There is occasionally a demand for a sheet steel which will form readily but develop a high tensile strength. For such applications the chromium-vanadium sheet steel S.A.E. No. 6130 or the chromium-molybdenum steel S.A.E. No. X4130 are used because they respond to heat treatment. The chromium-vanadium steel is now being displaced with the chromium-molybdenum steel which appears to be a more uniform and more easily manufactured product.

There are only a few applications for tubing on the engine. Some mild carbon tubing similar to S.A.E. No. 1025 is used for such parts as push rod housings. It is occasionally used for such parts as washers, oil slingers and special nuts. When a high quality material is desired the chromium-molybdenum steel S.A.E. No. X4130 is used because it responds to heat treatment. This alloy has been used for push rods and has been very satisfactory for this purpose.

Wire is used for miscellaneous springs throughout the engine. Some of these springs are subject to small stresses and function only intermittently. They may be made from ordinary carbon-steel spring wire V. When a high quality spring is desired it is made from music wire or chromium-vanadium spring wire S.A.E. No. 6150. Valve springs which are one of the most important parts of the engine and are continuously subjected to repeated stresses are made from either the chromium-vanadium spring wire S.A.E. No. 6150 or music wire. Both of these classes of wire have proved satisfactory in aircraft engines.

[For Discussion on Aircraft Engine Parts, see page 194.—ED.]

FAILURES OF AIRCRAFT ENGINE PARTS AND CAUSES THEREOF[1]

By Thomas T. Neill[2]

Synopsis

The material used as a basis for this paper was the information obtained during the two previous years of aircraft engine type testing, conducted by the Bureau of Standards for the Aeronautics Branch of the Department of Commerce. The paper describes numerous failures in various parts of the engines subjected to test, and explains the causes which were determined for these breakages. Separate sections are devoted to failures of the valve assembly, pistons, connecting rods, crankshafts, bearings, gears, crankcases and cylinders. Poor design is given as a more frequent cause of failure than faulty material.

The conclusion is drawn that lack of sufficient development work by the manufacturers is responsible for the large number of engines which fail during the tests. The great protection afforded to the public, by restricting the use of inferior engines, is pointed out.

The illustrations show some typical failures which have been encountered.

This paper is based upon information obtained from tests made under conditions specified in the Air Commerce Regulations and the facts are of value only under comparable conditions. The data used were collected in the last two years at the Bureau of Standards, during which time over 40 engine type tests have been made. These tests are conducted for the Aeronautics Branch of the Department of Commerce and it seems proper that a brief summary of the test procedure be given at this point.

The Air Commerce Regulations provide that the engines used in all licensed aircraft must be of a type which has been approved by the Department of Commerce:

> Engines which have passed the regular endurance test of and are approved by the United States Army Air Corps or the United States Navy will be approved for use in commercial aircraft. Other engines submitted for approval will be tested by the Department of Commerce at the Bureau of Standards. . . . Before an engine is submitted to the Department of Commerce for test, it shall be run by the manufacturer for at least 25 hours at a speed of not less than 90 per cent of that for which a rating is desired. Five hours of this test shall be run at full throttle.[3]

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[1] Published with the approval of the Director of the Bureau of Standards of the U. S. Department of Commerce, Washington, D. C.

[2] Assistant Engineer, U. S. Bureau of Standards, Washington, D. C.

[3] U. S. Department of Commerce *Aeronautics Bulletin No. 7-A*, Section II-1.

The block tests made at the Bureau of Standards, which conform in general to the corresponding Army and Navy tests, comprise (1) a 50-hour endurance test, and (2) a power-curve test. The former is run in ten 5-hour periods, the first of which must be at full throttle at a speed at least equal to the manufacturer's rated speed. The average power developed during this period is used as a basis for the rating. During the remaining nine periods the engine is run at approximately 97 per cent of the rated speed, giving a horsepower not less than nine-tenths of the rated horsepower. Minor repairs and replacements are permitted between periods and a maximum of three forced stops is allowed during the test. These latter require additional specified penalty runs. The power-curve test is made to determine the full throttle performance at various speeds and covers a range of from approximately 75 to 110 per cent of the rated speed. After the test has been terminated, either by successfully completing the run, by a major failure, or because minor failures have caused more than three forced stops, a complete teardown inspection is made to determine the general condition of the engine.

During the time that this type test work has been in progress, many failures have occurred in various parts of the engines under test. Usually rather definite causes can be found, but with only a single test as a background it is sometimes impossible to do more than guess as to what is the probable explanation.

Most of the engines tested have been of from 50 to 150 h.p. and of more or less conventional air-cooled radial design. There have been a few in-line engines and a still smaller number of other types.

The number of materials suitable for the various parts of similar types of aircraft engines is relatively small; and although it cannot be said that really suitable materials are always used, the different manufacturers do not seem desirous of showing very much originality in this respect. There appear to be, however, numerous possible satisfactory variations in design, many of which have value from the point of view of production or sales if not of operation, and hence the engines submitted for test have shown considerable difference in this respect. The result has been that even though material and design are interrelated, more failures may be charged to the latter than to the former.

The Bureau does not regularly make a metallurgical examination or a chemical analysis of parts which fail. Hence this information is usually obtained from the manufacturer and is assumed to be correct. The Bureau's recommendations in reference to improvements are always rather general, the responsibility for the details being left to the manufacturer who must later submit the final design for approval.

The Valve Assembly:

The valve assembly is one place where a particularly large number of failures have occurred. This is partially due to the excessive amount of trouble with springs that has been encountered in some instances. A few cases are on record of improperly hardened cams. Improper hardening resulted either in excessive wear or cracking. The former takes place during the test but the latter probably occurs in the manufacturing process. No evidence has been obtained in any of the tests of cams cracking during operation. Cam followers have given some trouble. The bearings of the rollers in one instance showed extreme wear due to poor material. The follower arms failed in another case due to the fact that they were not forged but were made from bar stock and then hardened. Very little trouble has been experienced with the push rods used on overhead valve designs, although rocker arms are a relatively frequent source of failure. Some manufacturers have made their rocker arms from bar stock and others have used a single die and then made "rights" and "lefts" by twisting. Both of these practices have resulted in failures. Many instances of poor design have been found ranging all the way from improperly designed sections to poor tappet adjustment locking devices. The rocker arm shafts gave trouble in one case due to the use of a light alloy altogether unsuited to this service.

Failures of valve springs are very common, more than a dozen having broken during a single test. Practically all of the engines submitted have been equipped with coil springs made from steel ribbon or wire, as many as three of those made from the latter material being used on an individual valve. Although a single failure where multiple springs are used may have no effect on the performance, such a breakage may be quite serious where only one spring is provided for each valve, especially in the case of engines having a small number of cylinders. The use of single springs and their subsequent failure have been responsible, at least in part, for the rejection of several engines having a small number of cylinders. It is not usually very convenient to use more than a single spring when ribbon stock is employed for the material. The jamming of such springs is likely to occur in case of failure with a possible injury to the push rod, rocker arm or cylinder head. The trouble experienced with this type of spring, however, has not been out of proportion to the number of engines using this design. Where multiple springs of the conventional wire coil type are used, very little trouble has been caused by a broken spring becoming entangled with the others of the same group. Surging is doubtless one cause of spring failure. Lack of uniformity of heat treatment and minute seams in the material are some other possible causes. There did not appear to be very much difference in the composition of the materials used for springs in a number of the engines tested, even though some were entirely satisfactory while others were just the reverse.

The failure of a valve is extremely serious and frequently results in completely wrecking the engine. Breakage usually occurs in the stem at the head of the valve or near the spring retainer. Figure 1 shows several breakages which are typical examples. Exactly the same material and heat treatment were used in two cases where the valves were almost identical. In one case failure occurred due to the reduction in wall thickness of the hollow stem caused by a poorly designed safety device, whereas the other was entirely satisfactory. Poor finish manifested by tool marks was the cause of failure in another case. The breakages which occur at the valve head are, of course,

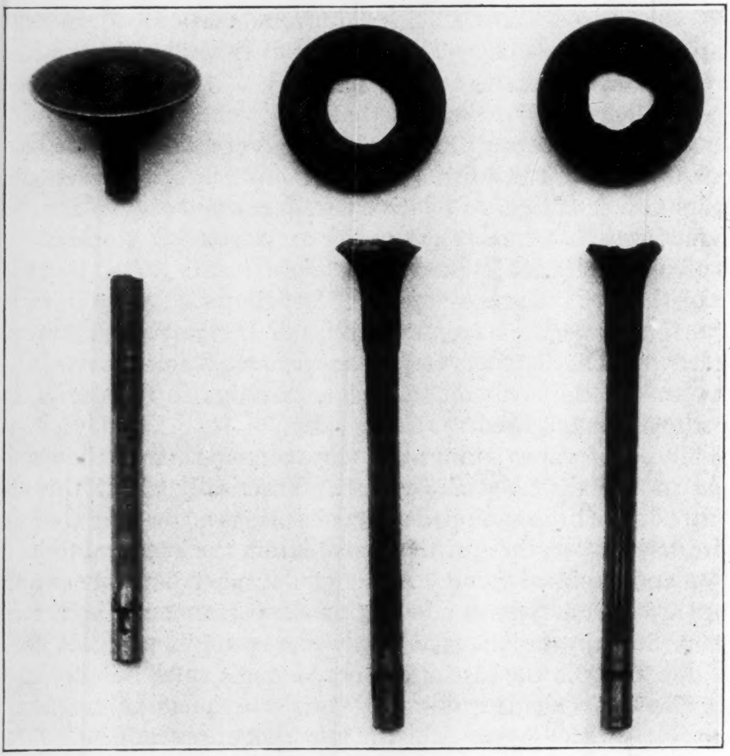

FIG. 1.—Typical Valve Failures.

influenced by the operating temperatures, whereas those which occur at the upper end are due primarily to repeated shock. While discussing valves it should be mentioned that excessive wear of the guides, as well as sticking, has been noted occasionally. One particularly bad case of wear was caused by the use of guides having graphite-filled grooves. The operating temperatures were relatively high and the graphite inlays disintegrated and left a greatly reduced bearing area which wore rapidly. Sticking valves have given very little trouble. In one case insufficient clearance which resulted in scoring of the stem was the only cause, no gumming being noted.

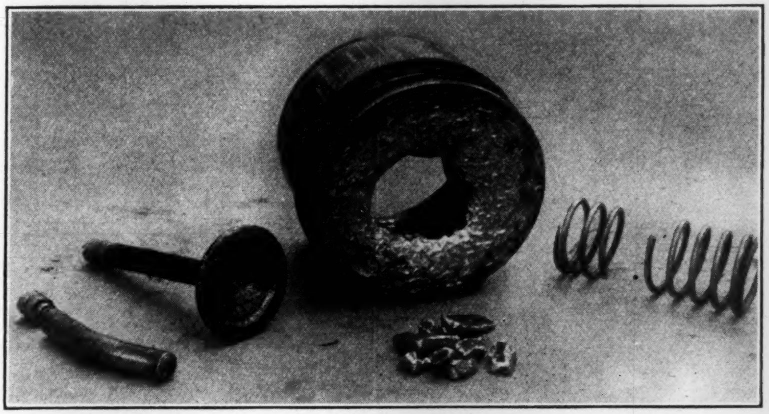

FIG. 2.—Typical Piston Failure Caused by Dropping of Valve.

The stem of the broken exhaust valve and the battered intake valve are shown at the left. A typical broken valve spring appears at the right.

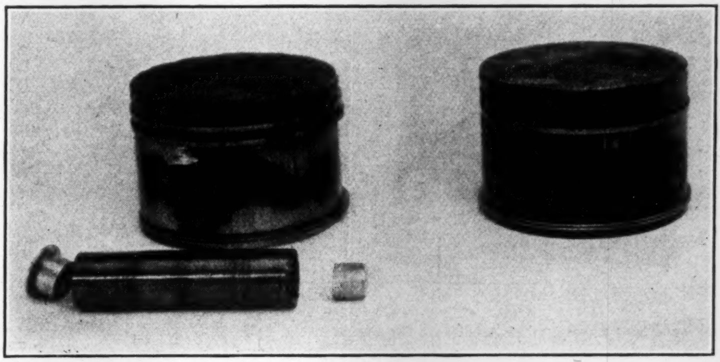

FIG. 3.—Piston Failures.

The end plugs for the piston pin shown at the left were originally the same size. The excessive wear was due to the use of unsuitable material. The piston at the right became overheated due to gas blowing by the stuck rings.

Wear of valve seats has not given much trouble, although warping of the cylinder heads due to poor design, which resulted in uneven expansion, has appeared in at least one instance. In another case, the valve seats wore until the spring retainers hit the rocker arm housings, but the clearance between the retainers and the housings was small. The material of the valve seats in this case was cast iron. It appeared, however, that not more than partial responsibility could be attributed to the use of this material.

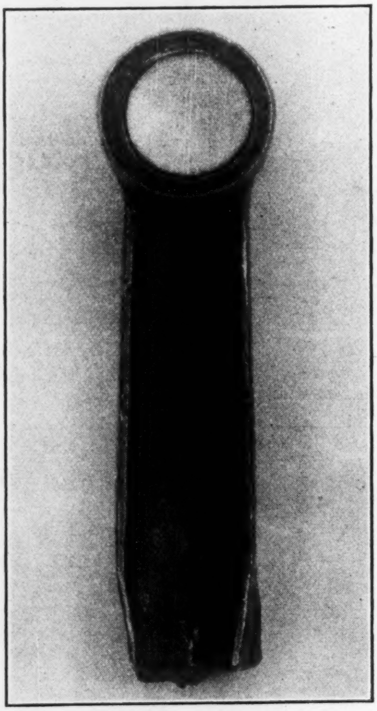

FIG. 4.—Broken Connecting Rod.
This was a poor forging as evidenced by the seams in the web.

Piston failure is frequently caused by the breakage of a valve in engines of the in-head type. If the stem breaks near the upper end, a suitable safety device may save the engine. In the cases noted, however, the safety devices were of no value.

Pistons:

Several engines have been completely wrecked by a broken valve crashing through the piston. Figure 2 shows an example of such a case. If the cylinder head is weaker under impact than the piston, the former may fail first, although this is not usually the case. Breakage caused by a valve cannot, of course, be charged against the piston. One odd case of failure was noted when the skirt of the piston collapsed. The collapse apparently was due to the design which called for a rather thin section at the lower part of the piston. Almost all of the engines submitted have been equipped with aluminum-alloy pistons and several cases of damage due to excessive temperatures have been found. This is primarily a problem of heat transfer, but mechanical failures such as ring breakage sometimes cause an otherwise good piston to overheat. The pistons shown in Fig. 3 were both somewhat overheated due to gas blowing past after the rings stuck.

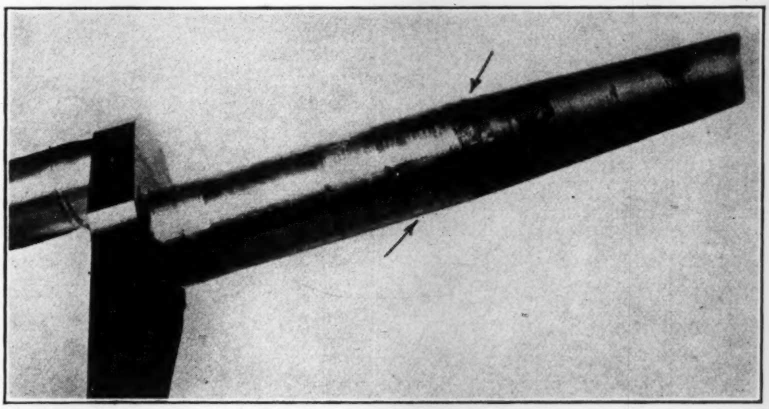

FIG. 5.—Crankshaft Failure.

The most common method of retaining the piston pins is to push plugs in each end and allow these to bear against the cylinder bore. This method is usually very satisfactory but the plugs must be made from suitable materials. Duralumin and aluminum bronze have given no trouble, but in some cases where soft aluminum bar stock was used, the plugs have worn away completely and allowed the pins to gouge the cylinders. Figure 3 shows two piston pin end plugs, one in good condition and the other badly worn. When such end plugs are only partially worn, they often work up and down and damage the piston around the outer end of the piston pin bearing. Some trouble has been experienced with piston seizure. The cause of the trouble is usually lack of lubrication, although insufficient clearance caused by growth of the piston castings has sometimes been responsible.

Connecting Rods:

Connecting rods have been the cause of very little difficulty, but they are frequently extremely heavy. Although several rods have failed, the cause has in only one case been directly traced to the rod itself. This rod was a very poor forging, as can be seen in Fig. 4, which shows the upper end of this part. Many manufacturers stamp the cylinder number on the shank of the corresponding connecting rod. Such practice on parts subject to repeated stress is to be condemned, marking with an electric "pencil" being much preferred.

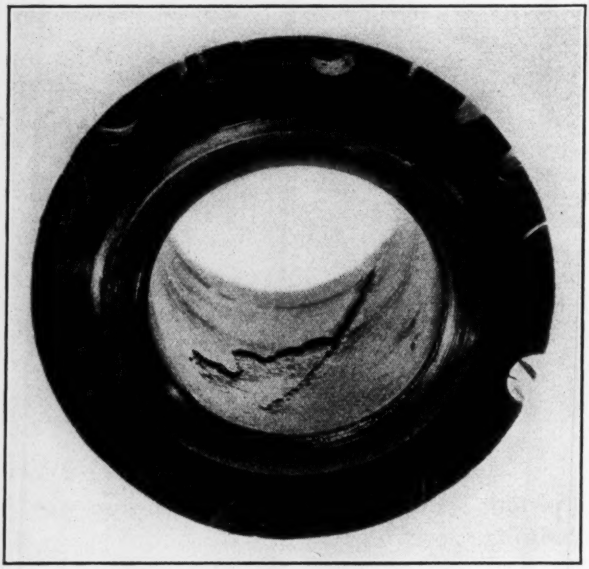

FIG. 6.—Master Rod Bearing Failure.

Crankshafts:

A few crankshafts have broken and although such failures are not common, they are doubtless the most serious from the point of view of danger. Like many other failures they wreck the engine, but in addition they are liable to permit the propeller to fly off or to tear the engine from its mounting, with a possible wreckage of the plane. Landing with a "dead" engine may be serious, but if in addition the wing or fuselage is damaged, conditions are far worse. Poor design and poor material, with the emphasis on the former, appear to have been the chief causes of the few crankshaft breakages which have occurred. Sharp changes of section in the crankshaft bore at a highly stressed part, keyways with sharp corners and with screw holes to hold the propeller keys are some of the features of poor design which have been noted. A typical crankshaft failure is shown in Fig. 5, but this particular shaft was not made according to the drawings. The cause of this failure was the absence of a suitable fillet in the keyway, together with a sharp change in the diameter of the bore of the shaft at the same point. In one case somewhat "dirty" steel was found when the crankshaft material was subject to a metallographic examination.

Bearings:

The crankshaft bearings used in most of the engines tested have been of the anti-friction type and as might be expected, no wear has been found, although the retainers have been damaged in a few cases. Plain bearings are generally used for connecting rod bearings and sometimes for radial-engine crankshafts. These are ordinarily of the bronze-backed babbitt type, and some trouble has been experienced with cracking of the bearing metal and separation from the backing. A typical example of this is shown in Fig. 6. Poor bonding between the babbitt and the bronze appears to be a common cause. One case was found where the babbitt was not cracked at all, although it had separated from the backing over a very large area. Poor fitting of the bearing, thus reducing the effective area, has been noted in some cases. Actual flexing of the rod itself under the bearing, to such an extent as to injure the babbitt, has been noted in only one instance.

Crankcases:

Crankcases have been of aluminum or magnesium alloys, and have failed on several occasions. In one instance a core apparently shifted when the crankcase was cast, the resulting section being so thin that it broke after about 25 hours of running. In another case improper design, where the cylinder studs were tapped in, was at least partially responsible for a failure. Cooling cracks, which should have resulted in rejection of the part by the manufacturer's inspection service, are sometimes found.

Cylinders:

Cylinder failures have been more common than might be expected. In two cases the bosses or flanges provided to secure the cylinders to the crankcase have broken. Cracks occasionally develop in the cylinder head and overheating due to insufficient cooling fin area has been determined definitely as the cause in one case. Poor heat treatment and inferior material were probably the major factors in another case where several aluminum-alloy heads failed.

Miscellaneous:

The magneto drives, which are provided by the engine manufacturers, have given some trouble. Poor design has always been the cause.

All of the accessories used on the engines submitted, which are purchased by the engine manufacturers from other concerns, have been made by a small number of companies, with the result that more or less the same type of equipment is employed.

Magnetos have given very little trouble.

Carburetors have failed somewhat more frequently. In one case a brass stamping failed at a bend of very small radius due to fatigue and possibly season cracking. The absence of suitable air heaters resulted in some carburetors freezing at the throttle.

Spark plugs are the cause of very little trouble considering the number used. Some engines will operate satisfactorily only on certain types of plugs, being particularly sensitive in this respect.

Starters are not usually supplied as standard equipment and are therefore seldom submitted for use during the test.

Minor failures are common, such as parts working loose, joints cracking, adjustments slipping, etc. In general the points covered are those which have been found frequently or which are particularly important.

CONCLUSIONS

The weaknesses which have been noted are for the most part those which should have been found and corrected during the manufacturers' development work. All of the engines submitted are supposedly ready for production and sale. Out of the first twelve engines tested only two passed; the builders of the others either resumed their experimental work or discontinued activity in this line. The protection afforded the flying public, as well as those over whom these engines might have flown, is very obvious.

This test work has also resulted in the building of improved commercial engines, thus helping the manufacturers to create new public confidence in the industry. Most of the engines recently submitted have passed the test, whereas formerly the reverse was true, although the test requirements have gradually been made more rigid.

The best of engines must not be abused. Those which have received Approved Type Certificates from the Department of Commerce, as listed in the Air Commerce Bulletins, are approved for certain speeds, and for use on fuels the anti-knock properties of which should be equal to or exceed given values. If these conditions are not fairly met, new failures not encountered on the test stand may be expected.

[For Discussion on Engine Failures, see p. 194.—ED.]

SPECIFICATIONS AND MATERIALS CONTROL[1]

BY H. A. BACKUS[1]

SYNOPSIS

Specifications are necessary for all materials of construction and finish and for all important shop processes such as heat treating, welding, plating, etc. Stock can also be classified conveniently by a properly developed scheme of specifications.

Inspection must insure (1) that the samples meet specification requirements and especially, (2) that the rest of the lot is like the samples. Emphasis is placed on making the proper kind and quantity of tests to show defects not apparent by sampling methods only. A series of recommended inspection tests is given for the more common aircraft materials.

Identification of approved materials must continue through stores and all shop handling. Mixed stock may be segregated as described.

In the general scheme under which the aircraft industry functions, the engineering and sales executives determine the types and characteristics of aircraft to be designed and manufactured. The plant departments function successively; the engineering department creating drawings and specifications, the manufacturing departments fabricating to these designs, following specifications and other directions, and the inspection department checking and comparing results with the original engineering drawings and specification requirements.

The importance of specifications and of materials control is evident. Carefully planned designs require as careful execution of the ideas involved and precautions and proofs may necessarily be somewhat detailed.

In the control of quality in aircraft, attention is usually directed to the tests and other inspection requirements which a given lot of material must meet. It is ordinarily assumed that samples taken from the lot accurately represent every other piece in that lot, but unfortunately this is not always true and the consequences may be serious. It is logical and necessary that we prove both (1) the ability of samples to meet requirements and (2) the equality between these samples and the remainder of the lot.

With the present types of aircraft the merit factor of strength divided by weight is most important so far as the structure is concerned. There are two factors of ignorance which handicap designs through excess weight. The first represents the ratio between the actual applied loads or developed stresses and the calculated loads or stresses. With more accurate aero-dynamic data and improved methods of calculation this factor will approach unity as a limit. The second factor of ignorance is represented by the ratio between the actual or developed strength and the desired or calculated strength. To decrease this factor safely requires complete knowledge and continuous control of materials and processes. If the airplane designer could be absolutely assured of complete uniformity in all materials of construction and in all manufacturing operations on these materials, he would find it possible and practicable to save considerable weight without changing the type of design or the specific strength of any materials. Wrought metals are relatively uniform, in comparison with castings, but a detailed inspection leads every metallurgist to the conclusion that all materials require careful watching. Let us, therefore, try to achieve uniformity and when this is accomplished, go on to raise the specific values of those materials in which we have gained uniformity of results.

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In the control of quality the first step is the specification of the factors desired. This is followed by control of the results through (1) inspection and tests (2) handling and storing of stock and identification thereof and (3) use of approved and standardized shop processes.

To specify is to be specific. Every order, every item of instruction or information, every item of procedure and practice should be specific. The ideal specifications should say exactly what is meant but in a more concise and well formulated manner than possible in verbal instructions. There still seems to be an antipathy toward specifications and inspection on the part of some "practical" men of the industry who mentally scoff at them but who at the same time demand the uniform high quality which these aim to insure. This somewhat parallels the human dislike for written laws and the police, while expecting that somehow without them perfect behavior will result even when conditions are unfavorable.

Specifications should cover all materials of construction and finish, and all important shop processes, such as heat treating, welding, plating, etc. The content of each specification may vary according to the importance of the subject. A system of specification numbers should be provided as a means of identifying even those materials and processes which are looked upon as ordinary or commercial, and these specifications should indicate at least the character of the material and as much more in the way of requirements and restrictions as may be desired.

There is an important point in considering a material specification number as a stock classification number. Many of the Army and Navy specifications are so general in nature that they cannot be used by number alone to indicate without qualifications any one of the several kinds or grades of material which they cover. For example, Army specification 57-136-8, for chromium molybdenum steel sheet or strip, specifies annealed material, but without indicating physical requirements in that state other than a bend test. It is also required that the material be capable of developing a tensile strength of 125,000 lb. per sq. in. with appropriate yield point and elongation after heat treatment. Much of this material is purchased in the normalized state, calling for 95,000 lb. per sq. in., minimum, in which condition it is sufficiently workable for general use. When used in designs at this strength no further heat treatment would be specified on drawings. Here, the Army specification number affords no means of fixing the strength of the material and there is therefore the possibility of using annealed material in production where normalized or heat-treated material was intended. It is necessary, therefore, to make a separate specification covering this type of steel when supplied at 95,000 lb. per sq. in. tensile strength. There are also instances where steels of different compositions, and requiring different heat treatments are permitted under a given set of physical requirements. By assigning a number which will properly differentiate between varieties in chemical analysis and mechanical properties a symbol for stock classification is arrived at which can be used on drawings and go through the production, inspection, stores, accounting and purchasing departments with surprising convenience and without danger of confusion.

In writing and interpreting specifications, due recognition must be made of (1) allowable variations from the desired normal and (2) the policy which determines the degree of quality control to be imposed. A specification implies that there is only one correct or preferred procedure, characteristic or material. This is not invariably true and there are some specifications in which allowable alternates are all equally acceptable and should be expressed when there is no desire to distinguish between them. Most of the Army and Navy specification numbers are unsuitable as stock classifications because they do include alternates which have to be treated as separate items by someone in the organization.

It is further necessary to bear in mind the policy governing a specification, so as to permit its interpretation to be consistent with the intention which created it. Otherwise, what may have been an arbitrary choice, and which should be interpreted as such, may seem unsuitable or incorrect when viewed from a different standpoint. The form and content of specifications will naturally be different if they include those factors pertaining to a local plant and the human shortcomings of its particular personnel. Specifications of a more general nature and applicable to many plants must be available, such as those of the Society of Automotive Engineers, the American Society for Testing Materials and the Army and Navy. It is necessary to go beyond these general requirements whenever special or local conditions make necessary more detailed checks on uniformity and where known tendencies of the personnel must be corrected.

Experience has proved that it is unsafe and misleading continually to put faith in superficial methods of inspection, or even in inspection at source by the vendor or by the Army or Navy inspectors. Repeatedly, extra tests of a type indicated later have shown non-uniformity to exist in a lot where everyone had expected satisfaction because tests by the sampling method has been acceptable. This is a serious matter where design is based on as close factors as must exist in aircraft construction.

In aircraft manufacture, specifications of materials, processes, finishes, heat treatments, etc., have three major uses: (1) as a part of purchase requirements; (2) as instructions to the shop; and (3) as a reference for engineering and inspection. The purchasing department operates most conveniently and most correctly if provided with a sufficient number of copies of specifications for distribution to vendors. The required characteristics of purchased articles and materials should be very definitely expressed in the purchase order, and reference to a drawing number or to a specification number will permit such definiteness with a minimum of writing on the order.

Shop instructions on special or standardized procedures should be given in specification form. This will advise all those concerned of the chosen methods of operation and will be most effective as a basis of control by inspectors. Absence of written instructions may allow individuals to vary from or to ignore the desires of the technical management.

Written specifications are also necessary as supplements to the drawings to transfer complete technical information and requirements from the engineering department to the inspection and other departments. The drawing should make definite reference to every written specification involved for, since specifications do not in themselves usually indicate the particular items of manufacture on which they are effective, it is necessary to indicate each time they are in effect or some control will be lost through possible variations in interpretation. To make such complete references on drawings convenient to the engineer requires the free use of specification numbers as a substitute for full written instructions on the drawing itself. There is common use of code numbers to represent (1) standard parts; (2) other drawings included as parts of an assembly; and (3) material specifications. It is logical to go further and use only numbered references of processes, heat treatments and finishes. Finishes, in particular, are subject to rather frequent revisions in materials or procedure and any instructions given in detail on drawings are constantly subject to change. A great advantage is gained if reference to all finishes on drawings is made by specification numbers only, as the content of the separate specification sheets can then be easily changed without requiring revision of the drawings themselves.

The following notes on the inspection and test requirements for purchased materials are given with the comment that the policy governing their selection was to emphasize more clearly than usual the degree of uniformity which can be secured by quality control, especially through inspection tests. As a class, engine manufacturers are much more careful and complete in their materials control than are the builders of the airplane structures. The former have their own details of control usually well worked out, but there is an amazing liberality in the viewpoint of many airplane manufacturers which in the author's opinion is not only dangerous to the users of their products but which has a restricting effect on the advance of airplane design as a whole.

It is so easy to assume that a lot of material is completely satisfactory that no effort is made to give the lot a careful recheck, relying wholly upon the results of inspection at source or upon a few sample tests at destination. It is the experience of those who have taken the trouble to investigate on their own account that with more detailed inspection methods they find more facts which allow them not only to reject material but also to correct their procedure and so improve the product. At least such precautions give information upon which decisions of policy and the necessary extent of tests can be more accurately made. The requirements indicated may seem too rigorous but experience has often proved their worth. In airplane manufacture there is general agreement that quality is paramount, but there are many examples of unheeding or ignorant violation of the means by which quality control is accomplished.

The following materials should be purchased in general accordance with the specifications indicated, but only the essential inspection tests noted need be applied as routine procedure unless special conditions seem to require further investigation, provided the consent of the government inspector is previously secured on government work. It is expected that materials will be purchased only from those vendors who have proved satisfactory in the past and the uniformity of whose product is not in question. For simplicity, only Army specifications are referred to, but there are generally corresponding ones in the Navy series. Either of these are worthy guides for the best commercial practice. In addition to the tests indicated below, the usual inspection checks for dimensions, for visual inspection of surfaces, etc., should be made.

Aluminum and Aluminum Alloys:

Identification Tests.—(*a*) *Caustic etch.* Spot or immersion 10 per cent NaOH. Black deposit shows presence of copper, indicating Dural, 17s, 25s, 8 per cent copper-aluminum and heat-treated aluminum-alloy castings and all other copper-bearing alloys. Shining white appearance indicates aluminum, including aluminum coating of "Alclad" 17S. If a gray deposit results, the material should be heat treated to make the test definite. Rate of attack and darkness of surface is a function of heat treatment and copper content. If immersed, wash with water, neutralize with nitric acid and wash thoroughly in water again.

(*b*) *Hydrofloric acid etch* (10 per cent HF).—Similar general action, but cleaner. On annealed stock, action is slower and more spotty and color is lighter gray than on heat-treated stock. Alloy 25S gives slower action and larger bubbles with more tendency to pit than does alloy 17S. Wash as for caustic etch.

In examination of aluminum-alloy products, use of an all-over etch for the whole lot is very desirable, particularly for castings, tubing and for larger sizes of bar stock.

Bars, Aluminum.—Specification 57–171—(*a*) Identification. This is necessary to prevent duralumin or other types of material accidentally being used for parts which are to be welded, as for gas tanks, etc.

Bars, Duralumin.—Specification 57–152A—(*a*) Tension (*b*) bend (*c*) chemical. The vendor's certificate of chemical analysis is generally acceptable. (*d*) Etch all bars of large size. It is highly desirable to etch the separate pieces which are cut from the bars from which machined parts are to be made. Examination should be made not only at this time but also at some later stage during or following complete machining so that the true character of the material which will be left can be definitely known.

Castings, Aluminum-Alloy.—Specification 57–72 Grade 1—5-per-cent silicon alloy—(*a*) Chemical analysis, for silicon only, as identification. This test will insure proper grade of material for gas tank and other welded parts.

Castings, Aluminum-Alloy.—Specification 57–72 Grade 3—Lynite No. 195—or Bohnalite B—(*a*) Tension (*b*) brinell hardness, 10 per cent of lot, or 100 per cent depending on quantity and importance, (*c*) Etch, all castings.

Castings, Aluminum-Alloy.—Specification 57–72 Grade 5—8 per cent Copper—(*a*) Destruction of samples by testing machine or by hammer and vise method. This is a very satisfactory indication of the general strength, ductility and quality of the metal in the castings themselves instead of in the test bars. (*b*) Etch, all castings.

Small Forgings, Aluminum-Alloy.—Specification 57–153—(*a*) Brinell or Rockwell hardness, each piece (*b*) tension, one per heat-treated lot (*c*) chemical, vendor's certificate sufficient. This does not apply to propellers.

Rivets, Dural.—(*a*) Identification of sample. If lots as purchased or as found in the shop are suspected of being mixed, use a basket for dipping in an etching solution and wash and dry for separation of dural and aluminum rivets. Acid treat and wash the separated lots. (*b*) Shear test, heat treated.

Sheet, Aluminum.—Specification 57–151—(*a*) Identify by spot etch test, each sheet.

Sheet, Duralumin.—Specification 57–152A—(*a*) Tension, heat-treated (*b*) bend, annealed, or as received (*c*) identification by spot etch test, each sheet.

Alclad (17S).—Specification 11059—(*a*) Tension, heat-treated (*b*) bend, annealed, or as received (*c*) identification spot etch test on each sheet. This must be applied on the edge in order to show the presence both of the aluminum coating and the duralumin core.

Tubing, Aluminum.—Specification 57–186–1—(*a*) Identification by spot etch test.

Tubing, Duralumin.—Specification 57–187A—(*a*) Tension (*b*) flattening test (*c*) chemical, vendor's certificate (*d*) Etch each tube, for visual inspection, (*e*) Hardness, each tube.

Wire, Welding, Aluminum Silicon.—Specification 57–204A–1—(*a*) Chemical, silicon only.

Steel and Other Ferrous Metals:

Aircraft structural steels are principally S.A.E. Nos. 1025, 2330, 4130 or 4130X, and 6150. Aside from routine sample testing, the important point again is to check uniformity of each lot. The chief trouble is to see that No. 1025 stock is not mixed with No. 1015 and No. 1020 and that the alloy steels are not mixed with any of these carbon steels as well as other varieties which may accidentally have been included in the lot through careless handling. To this end some test should be applied to each piece of alloy steel bar, sheet or tube as a matter of receiving stores inspection. Of course 100 per cent hardness inspection on the heat-treated parts will check the presence of alloy steel and the correct heat treatment thereof, but it is more economical in time and in money to proof check the individual bars, sheets and tubes before cutting up and working in manufacture.

All steel bars should be individually inspected and tested because (1) mixed lots are not unknown and are very costly, (2) defects which are reasons for rejection are more easily caught and more accurately estimated through a quantity of tests than by a single sample, and (3) items which may vary from bar to bar, such as pipes, seams, laps and possible surface decarbonization may be more definitely caught and segregated. The growing use of the deep etch test is of real value and it well repays the initial trouble of inspection. Engine manufacturers as a class pay more attention to these extra tests than do airplane manufacturers, but it is just as profitable for the latter to discover all defects because of the necessity of increasing the uniformity as well as the high performance of all materials with which they deal.

Bar, Steel, S.A.E. No. 1025.—Specification 57-107-9—(*a*) Chemical, phosphorus and sulfur only (*b*) tension, as received (*c*) tension, normalized.

Sheet, Steel, S.A.E. No. 1025.—Specification 57-136-3—(*a*) Chemical, phosphorus and sulfur only (*b*) tension, as received (*c*) tension, normalized (*d*) bend.

Tubing, Steel, S.A.E. No. 1025.—Specification 57-180-1A—(*a*) No chemical (*b*) tension, as received (*c*) tension, normalized (*d*) crushing test. Material for exhaust stacks and lugs for split clamps need not be tested.

The carbon and manganese content in No. 1025 steel is very well indicated by response to the normalized tension test, which further shows the effect of heating and cooling after welding. Nos. 1015 and 1020 stock, which in the cold-drawn condition will meet the "as received" tension test, will easily be discovered by the normalized test.

Bar, Steel, S.A.E. No. 2330.—Specification 57-107-17—(*a*) Chemical (*b*) identification by dimethylglyoxime spot test on each bar[1] (*c*) deep etch and Rockwell hardness test on heat-treated slug cut from end of each bar. It is important to check uniformity of each lot because of the frequency with which both mills and jobbers mix the stock. This cannot be satisfactorily discovered in the sample tests.

Bar, Steel, S.A.E. No. 6150.—Specification 57-107-5—(*a*) Chemical (*b*) deep etch and Rockwell hardness, heat-treated slug from end of each bar.

Bar, Steel, S.A.E. Nos. 4130 or 4130X.—Specification 57-107-19—(*a*) Chemical (*b*) tension, normalized (*c*) deep etch and Rockwell hardness, test heat-treated slug from end of each bar.[2]

Tubing, Steel, S.A.E. No. 4130X.—Specification 57-180-2A—(*a*) Chemical, carbon and chromium only (*b*) tension, as received (*c*) tension, normalized (*d*) deep etch, slug cut from each tube which is to be worked, as for tubular rivets, or flattened, bent or riveted members. Simply flatten both ends of each small tube to help select tubes of this size for their general workability (*e*) Rockwell hardness test on each tube, with minimum values of B90. For specification material it is absolutely necessary to be sure of the stock. Certain manufacturers of this tubing already use 100 per cent Rockwell tests as routine inspection.[1] Tubing purchased from jobbing dealers is much more likely to be mixed because of the rehandling done and purchases from these sources should be rechecked.

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[1] Nickel identification spot test (Disston formula):

1. Clean off all rust, scale and grease.
2. Apply one drop of 2:1 nitric acid for about 10 seconds.
3. Apply one or two drops of 2:1 Tartaric acid.
4. Apply one or two drops of dimethylglyoxime solution. (5 g. dimethylglyoxime; 225 ml. NH_4OH, 175 ml. H_2O).
5. Absorb with filter paper and dry. A red ring around a brown center indicates nickel present. A brown color alone indicates no nickel present.

[2] Each piece of a lot of heat-treated material requiring Rockwell testing should be given a single value which may be the mean of selected Rockwell readings, discarding those affected adversely by conditions indicated below. The single value may then be compared with the inspection values specified and acceptance so determined.

Low Rockwell readings may occur as the result of:

1. Badly decarburized surface condition.
2. "Spring" of the part itself, especially when a tube.
3. Improper adjustment of the piece on the anvil, so that "rocking" under the application of load may occur.
4. Scale either directly under the penetrator or in contact with the anvil.
5. Imperfect material or heat treatment. This last assumption is only justified when the foregoing causes are positively known not to exist.

Sheet, Steel, S.A.E. No. 4130X.—Specification 57–136–8—(*a*) Chemical (*b*) tension, normalized (*c*) bend for sheets less than ⅛ in. thick (*d*) Rockwell hardness, heat-treated corner cut from each sheet. This Rockwell test will check not only the uniformity of the lot but its response to heat treatment and also the presence of surface decarburization which may affect either one or both sides of the sheet. If low Rockwell readings are found, further investigation of the edge areas of the whole sheet should be made. Surface decarburization occurs principally along the margin of sheets and is discoverable conveniently by the above tests. It is important to eliminate all sheets so affected because lugs cut from these edges may have their strength seriously reduced below that of the rest of the fitting due to lowered carbon content, a very local defect.

Castings, Steel.—Specification 57–64A Grade 2—(*a*) Tension (*b*) Brinell hardness on 100 per cent of lot (*c*) X-ray inspection is the only method of assuring 100 per cent proof of the quality of individual castings.

Castings, Steel, Manganese.—Specification 57–65—(*a*) Certificate from vendor certifying chemical analysis and heat treatment sufficient for tail skid castings.

Forgings, Steel.—Specification 57–105—(*a*) Chemical analysis (*b*) deep etch on section of the sample (*c*) tension, Rockwell or Brinell hardness and other tests as necessary.

Protective Coatings:

Cadmium Plate.—Stripping test for thickness of coating. This should be a routine test by purchased lots and frequently applied to shop products.

Textile Products:

Cloth, Mercerized Cotton, Grade A.—Specification 6–97A—(*a*) Neutralization (*b*) thread count (*c*) weight (*d*) breaking strength.

Plywood.—Specification 82–6A:

(*a*) Shear test dry (*b*) Shear test wet.

The practice of picking the plies apart with a penknife is of disputed value but sometimes reveals interesting facts such as shiny non-glued areas. The general brittleness of plywood and the presence of local defects is easily checked by giving hand torsion tests, either to destruction or as a proof load of members like rib webs.

Glue—Certified Casein.—Specification 98–14020D:

(*a*) Adhesiveness, four specimens (*b*) waterproofing, two panels, cut each into 24 specimens. Casein glue tests are particularly susceptible to changes in condition of preparation, including all factors in mixing the glue, settling time, preparation of wood surface, clamping pressure and time. The specification requirements are easily met with proper glue and conditions of test.

Control of quality through correct marking, handling and storing of materials is important in that it preserves the identity and safe-guards the condition of tested and accepted materials. Identification of bar and tube stock is best accomplished by a single paint stripe of solid color extending the full length. This permits any small length to be positively recognized as to material. Sheet stock should also have a single color marking, either several diagonal stripes or a frequently repeated stencil giving the lot or laboratory number of the sheet. Such a number can also be applied to bar stock by a steel stamp on one end or near it, but should not take the place of the color marking.

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[1] H. C. Knerr, "Identification of Aircraft Tubing by Rockwell Test," *Technical Note No. 342*, National Advisory Committee for Aeronautics, June, 1930.

Mixed stock is most easily prevented if (1) check tests as outlined above are made on each piece and if (2) single color marking is accurately done by inspection before stocking. Bar stock can, however, be later mixed since the complete removal of the surface and surface paint in machining allows unauthorized substitution of a different material if supervision is at all careless. Mixed stock requires some ingenuity in sorting if positively safe results are to be secured with the least possible trouble. Some chemical identification tests can be quickly made. A convenient floor method of separating alloy steel from low-carbon steel and duralumin from aluminum is to heat a small piece in a welding torch flame and quench it in water. The duralumin or aluminum should be heated almost to the melting point. The wide differences in stiffness, brittleness and hardness make for easy identification. The color or surface condition of cold-rolled steel and duralumin is not a reliable means of checking the kind of material.

The influence of specifications and materials control is evident throughout all inspection activities. Beyond the features already covered there are programs rich in detail which govern in-process operations and inspection. These are matters of local requirements combined with good general practice. Opportunity does not permit going into the details of such in-process work, but such procedures should always aim at (1) keeping track of the identity and physical or other features already established and (2) checking new changes involved since the last check.

[For Discussion on Specifications and Materials Control, see page 200.—ED.]

MECHANICAL TESTING OF AIRCRAFT MATERIALS

By J. B. Johnson[1]

The mechanical testing of aircraft materials follows as closely as possible the standards which have been adopted by the American Society for Testing Materials. Modifications and extensions of these methods have been developed and applied to accommodate special types and forms of material used in aircraft construction. Only those tests are described which are performed in connection with the inspection of materials to determine their conformance to specifications.

Tension Tests

The tension test is used very extensively for all types of aircraft material except timber. The forms of test specimens which have been adopted for ferrous and non-ferrous metals are shown in Figs. 1 and 2. Within the capacity of the testing machine, bars, rods, wires and tubes are tested on specimens with the full cross-section, using a gage length of four times the diameter or distance across flats for circular and hexagonal stock, 10 in. for wire and 2 in. for tubes. The distance between the jaws with the specimen inserted is not less than the gage length plus two times the diameter. No elongation is measured on wires under about $\frac{3}{8}$ in. For rounds exceeding $\frac{3}{4}$ in. in. diameter and flats greater than $\frac{3}{4}$ in. in thickness, a test specimen conforming to Fig. 1 is used. For bars up to $1\frac{1}{2}$ in., the axis of the test specimen is located midway between the center and surface of the piece. Flat bars less than $\frac{3}{4}$ in. in thickness are machined to conform to Fig. 2 with a 4-in. gage length.

Samples for tension tests are cut both lengthwise and crosswise from sheets and strips over 6 in. in width. Shearing is permitted provided the metal is removed at least $\frac{1}{4}$ in. beyond the edge in machining the test specimen. The test specimen conforms to Fig. 2. A 2-in. gage length is standard practice, although 4 in. is optional and is often used by the sheet steel manufacturers. The sheet specimen is used for large tubes. It is cut without flattening the tube and the ends are then flattened for gripping. The width is taken as the length of the convex arc measured with a flexible scale. It is important that the gage length be given a slight taper and that the radius

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[1] Chief, Material Section, Materiel Division, Air Corps., U. S. A., Wright Field, Dayton, Ohio.

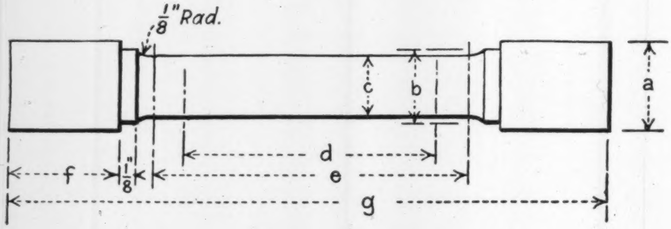
$\frac{1}{8}$" Rad.
c
b
a
d
f
$\frac{1}{8}$"
e
g

FIG. 1.—Round Tension Test Specimen.

	Over $\frac{3}{4}$ in. in Diameter	$\frac{1}{2}$ to $\frac{3}{4}$ in. in Diameter	$\frac{3}{8}$ to $\frac{1}{2}$ in. in Diameter	$\frac{1}{4}$ to $\frac{3}{8}$ in. in Diameter
Dimension *a*, in.	0.750	0.500	0.375	0.250
Dimension *b*, "	0.594	0.391	0.281	0.172
Dimension *c*, "	0.500	0.375	0.250	0.125
Dimension *d*, "	2.000	1.500	1.000	0.500
Dimension *e*, "	2.25	1.750	1.250	0.750
Dimension *f*, " (approx.)	1.00	0.750	0.500	0.375
Dimension *g*, " (approx.)	4.75	3.625	2.625	1.875

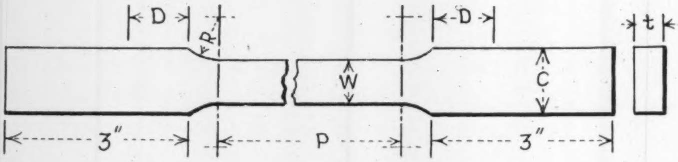

FIG. 2.—Flat Tension Test Specimen.

	Thickness, *t*, $\frac{1}{4}$ in. and under	Thickness, *t*, over $\frac{1}{4}$ in. to $\frac{1}{2}$ in., inclusive
Gage length, in.	2 or 4	2 or 4
Dimension *P*, in. (min.)	$2\frac{1}{4}$ or $4\frac{1}{2}$	$2\frac{1}{4}$ or $4\frac{1}{2}$
Dimension *R*, in. (min.)	$\frac{1}{2}$	$\frac{3}{4}$
Dimension *C*, in. (min.)	$\frac{3}{4}$	$1\frac{1}{8}$
Dimension *W*, in. (min.)	$\frac{1}{2} \pm 0.01$	$\frac{3}{4} \pm 0.015$

NOTE 1.—Specimens shall be reduced in width *W* at center of gage length (by draw filing) not more than 0.004 in. when *W* equals $\frac{1}{2}$ in., and 0.006 in. when *W* equals $\frac{3}{4}$ in.

NOTE 2.—The distance *D* between end of gripping jaws and the shoulder of specimen shall not be less than the gage width *W*.

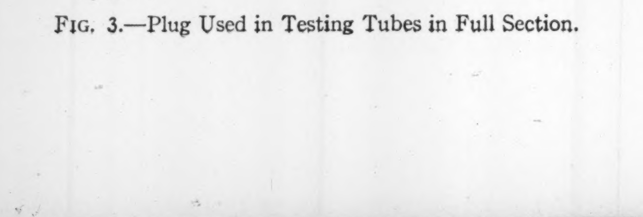
2" Min. to 6" Max.
$D_1 + \frac{1}{32}$"
Rad.=2D_1 approx.
D_1
$3\frac{1}{2}$ D
$\frac{1}{8}$"
$\frac{1}{4}$"
$\frac{3}{4}D_1$ to D_1 approx.
Plug to be Snug Fit in Tube
End Shape Optional

FIG. 3.—Plug Used in Testing Tubes in Full Section.

between the end and the reduced portion is not less than the width. The precautions to be observed in machining the sheet specimen have been brought out by Templin[1] and by Committee E-1 on Methods of Testing.[2]

Horizontal scratches and deep gage marks may cause premature failure with low elongation, especially on aluminum alloys and heat-treated steel less than 0.065 in. in thickness. The thickness of the test specimens must be carefully measured at several points with micrometers, as a difference of each 0.001 in. on a specimen 0.031 in. in thickness will cause a variation of 3 per cent in tensile strength and yield point which may become appreciable on material heat-treated to 200,000 lb. per sq. in.

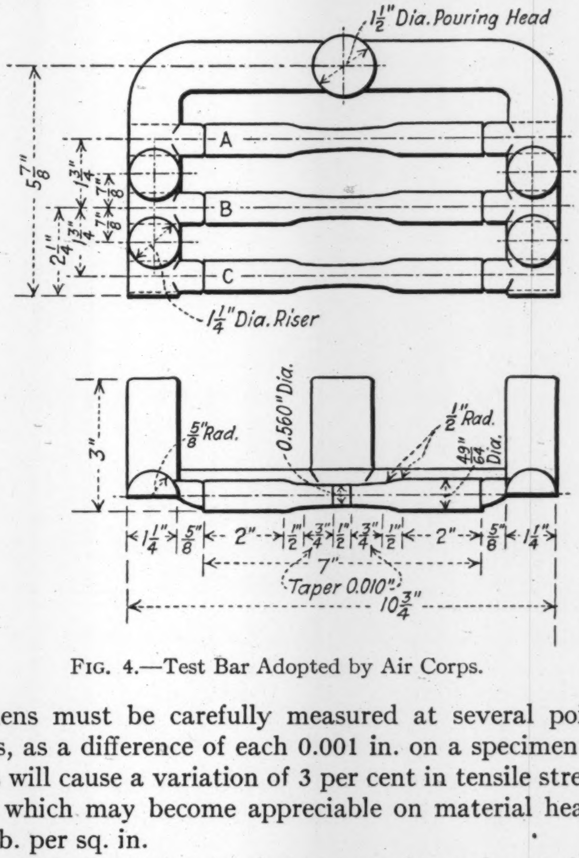

FIG. 4.—Test Bar Adopted by Air Corps.

The method of gripping tension test specimens has an important bearing on the results. It is essential that the loading be axial, which depends upon the alignment of the testing machine and the distribution of pressure over the ends of the specimen. This is accomplished in the case of thin sheet metal by using special grips.[1] The specimen is inserted so that the distance from the shoulder to the edge of the grips is at least equal to the width of the specimen. In the case of tubes tested in full section, snug fitting plugs are used. The plug extends beyond the edges of the grips, an amount equal to the diameter of the tube. The end of the plug is tapered to avoid interfering with the necking down of the tube, or rounded as shown in Fig. 3. The speed of testing should be such that the machine is always balanced with minimum vibration of the pointer or beam. In the case of hydraulic machines, this control is obtained without difficulty and the speed for testing thin sheet is about 0.025 in. per minute. In the case of screw machines, the lowest speed available should be used up to the yield point.

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[1] R. L. Templin, "Methods for Determining the Tensile Properties of Thin Sheet Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part II, p. 235 (1927).

[2] Report of Committee E-1 on Methods of Testing, *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part I, p. 502 (1926).

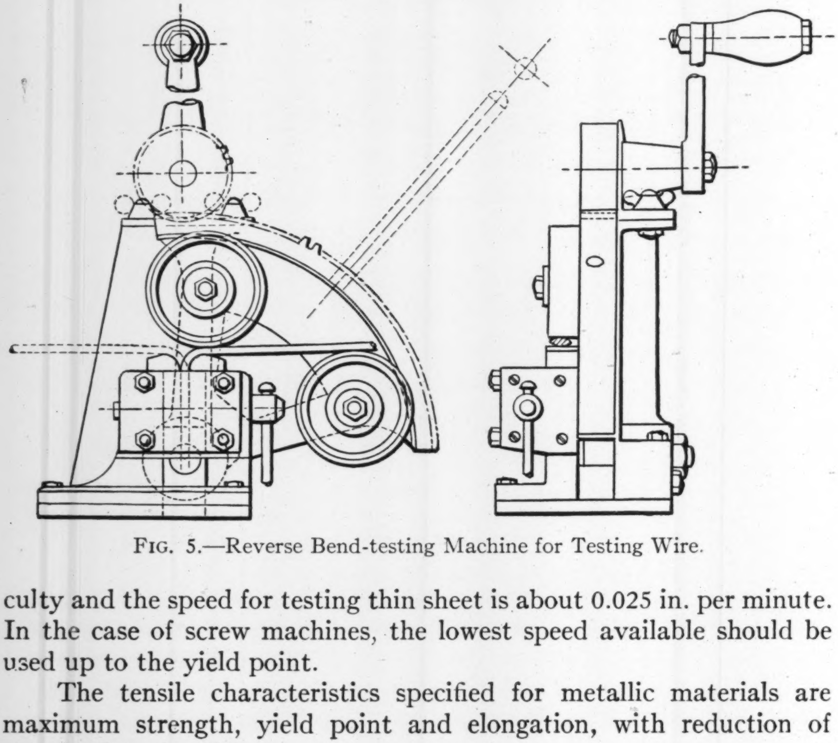

FIG. 5.—Reverse Bend-testing Machine for Testing Wire.

The tensile characteristics specified for metallic materials are maximum strength, yield point and elongation, with reduction of area in the case of bars.

The yield point can ordinarily be obtained with sufficient accuracy by the drop of the beam or lag of pointer or by dividers set for a predetermined extension. The extension can be made a function of the modulus of elasticity which is preferable to an arbitrary value. A total extension of 0.005 in. per inch is quite satisafactory for heat-treated aluminum alloys or chromium-molybdenum steel, but in the case of mild carbon steel 0.003 in. per inch more nearly checks the drop-of-beam method.

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[1] R. L. Templin, "Methods for Determining the Tensile Properties of Thin Sheet Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part II, p. 235 (1927).

In the case of heat-treated aluminum alloy castings, the tensile strength is obtained on sand-cast bars generally cast three in a mold. The type of bar adopted by the Air Corps is shown in Fig. 4. No machining is done prior to testing. The properties recorded are maximum strength and elongation in 2 in.

The procedure for testing texile and rubber products conforms to the Society's Methods D 39 – 27 on Testing Woven Textile Fabrics, strip method, and D 15 – 24 on Testing Rubber Products, respectively.

BEND TEST

There are two types of bend tests used in testing metallic aircraft materials, (1) single bend, and (2) 90 deg. reverse bend.

The single bend is made on bars and sheet as a qualitative indication of the fabricating properties. Bend tests on thin sheet, wires and small bars are easily made in a vise. The jaws of the vise should be rounded to prevent the edge cutting into the specimen on the inside of the bend. The operation should be completed by squeezing in the vise or hammering with a mallet until the legs of the specimen are parallel and in full contact with each other or a filler equal in thickness to the specified diameter of the bend.

Bends on heavy bars can be made over supports in a compression testing machine or by wiping around a pin. The use of a large contact area on the ram to start the bend avoids local crushing of the specimen. Constraint at the ends should be reduced by supporting on rollers.

The 90-deg. reverse bend is used as a measure of the ductility and toughness of material. It is used principally for wires and a machine developed for this purpose is shown in Fig. 5. The wire is forced by the rollers to make a full 90-deg. bend.

HARDNESS TESTS

Hardness tests are used in order to determine the uniformity between individual pieces in a lot of material and also to differentiate between carbon and alloy steels.

The Brinell test is used for castings, forgings and bars of large cross-section. The 500-kg. load is generally specified for non-ferrous parts, but a 1000-kg. load is used to some extent for aluminum alloy castings and forgings. The load is maintained for 30 seconds for copper and aluminum-base alloys and 60 seconds for magnesium-base alloys. In the case of steel, the 3000-kg. load is maintained for 15 seconds.

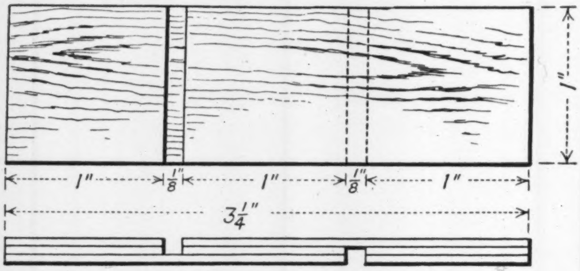

FIG. 6.—Shear Specimen for Testing Strength of Glued Joints.

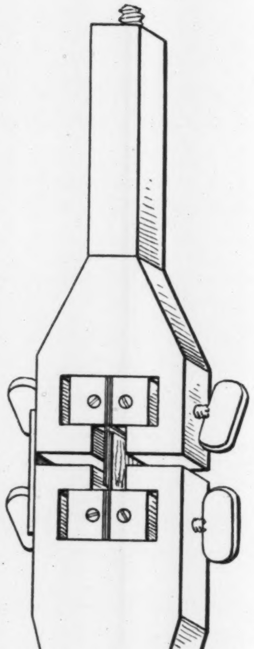

FIG. 7.—Jig for Testing Shear Specimen for Strength of Glued Joints.

The Rockwell hardness tester has a wider range of application than other methods of hardness testing since most of the wrought material is less than $\frac{1}{8}$ in. in thickness. This test is used for thin-walled tubing by adequately plugging and supporting the overhanging tube. The Rockwell hardness, "B" scale, taken with a $\frac{1}{16}$-in. ball is preferable to the diamond point although the latter may be used with the 60-kg. load. The Rockwell hardness, "E" scale, taken

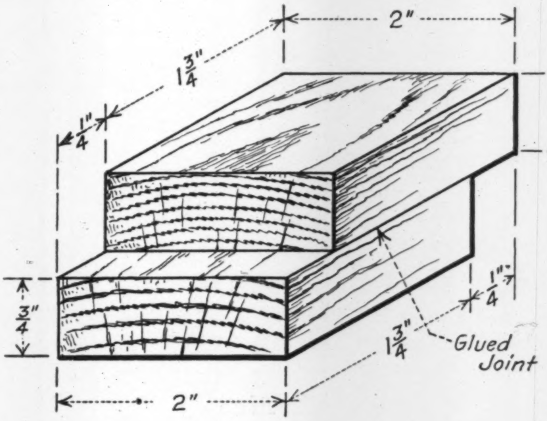

FIG. 8.—Shear Specimen for Testing Glue Adhesiveness.

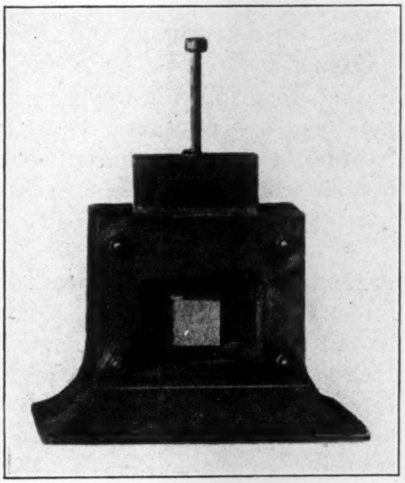

FIG. 9.—Jig for Testing Shear Specimen for Glue Adhesiveness.

with a $\frac{1}{8}$-in. ball is used for castings but the readings are more erratic than the Brinell tests.

The scleroscope is used for case-hardened parts.

The hardness test does not indicate quality. Overheating an aluminum casting during heat-treatment may lower the elongation and tensile strength 50 per cent without affecting the hardness. It is no criterion of ductility or structure in the case of ferrous metals.

IMPACT TEST

The impact test is suitable for detecting brash timber and has been used for this purpose in special cases, but has not been made a requirement of materials specifications. An unnotched specimen is used with either the Forest Products Pendulum Impact Tester or the Charpy Tester (23 ft-lb.).

The notched-bar impact test for forgings has a limited application as a criterion of the quality of steel as affected by heat-treatment. The Izod impact is generally specified. No specimen has been standardized.

SHEAR AND TORSION TESTS

Shear tests are used for determining the strength of glue joints. The form of test specimen and testing jig is shown in Figs. 6 and 7. The ends of the specimen are gripped in the jaws and the load applied at the rate of 600 to 1000 lb. per minute. This test is made before and after soaking in order to check the water-proofness of the glue.

A shear specimen for testing glue adhesiveness is shown in Fig. 8. This is placed in a special jig, Fig. 9, and the load applied in a compression machine.

Torsion tests are specified for small wires, such as music wire and spring wire, in order to detect hard spots, seams and other defects. The test specimen is not less than 10 in. in length with 8 in. between clamps. A small tension load is applied to prevent the wire from kinking. The wire is twisted at a uniform rate not exceeding 60 revolutions per minute. The machine must have one movable head to allow for the shortening of the specimen. The number of twists at which the specimen fails is recorded.

[For Discussion on Testing, see page 200.—ED.]

METAL JOINTS IN AIRCRAFT CONSTRUCTION

By T. Watson Downes[1]

Synopsis

The technique in making joints of the more important metals used in airplane construction by each of the methods of welding, brazing and soldering, with particular attention to the respective practices employed at the Naval Aircraft Factory, is briefly described.

Data on the tensile properties of oxyacetylene welds of the grade of chromium-molybdenum steel known as S.A.E. No. 4130X made with low-carbon welding rod and with parent metal, both as welded and after heat treatment, are given. The results of recent tension tests of oxyhydrogen welded and electric spot welded joints of duralumin sheet, before and after heat treatment, are also presented. Numerous applications of welding in aircraft structures are cited and the microstructure of welded chromium-molybdenum steel, also welded fittings, spot welded stainless steel wing-rib and welded aluminum gasoline tank construction, are illustrated.

Strength values of brazed, soft soldered and silver soldered joints, with mention of applications of these types of joint, are included. Soldering of aluminum and riveting are briefly discussed and shear values for rivets for use in design work are given.

In resistance to corrosion, brazed joints of steel, because of their tightness and the consequent exclusion of moisture, are considered to be highly efficient. Physical differences always obtain in the metal in and near a weld and for this reason welded joints are more or less subject to corrosion by electrolytic action. By suitable heat treatment it is possible to greatly reduce, but not entirely eliminate, the susceptibility of welded joints to this form of corrosive attack.

The methods in common use for effecting joints of metallic materials throughout aircraft structures include principally those three which involve the fusion of one or more metals, namely, welding, brazing and soldering, and that of riveting. It is the purpose and scope of this paper to outline as briefly as possible the usual procedure in these operations, to present data on the various characteristics of such joints and to enumerate and discuss the particular applications and conditions to which each type of joint is peculiarly adapted. Special attention will be given to the experience of the Naval Aircraft Factory in the production of joints, the results of tests thereof and the mention of specific cases in the construction of Naval aircraft for which each type of joint has become more or less standard.

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WELDING

Welding in aircraft manufacture is divided into the two main classes of gas welding and electric welding. The great majority of all welds of steels, aluminum and aluminum alloys are made by the gas method, although there is reason to believe that the application of electric welding will grow.

Steel Welding:

In gas welding steel, precautionary measures must be taken to allow for movement or warping of the parts to be welded due to the action of the heat. "Tacking" and the use of welding fixtures usually prove satisfactory. Good joints of thin sheets and tubes may usually be made without preparing the edges to be joined. The edges of parts of heavier gage material (over about $\frac{1}{8}$ in.) should be beveled at about 45 deg. A neutral flame should be used and should impinge on the work at such an angle and in such a direction that preheating of the work to be welded is accomplished as the weld advances. The welding rod is held at an angle to the work and fed to the weld at the proper rate to produce a moderate excess of metal along the joint. The size of the welding rod depends principally upon the thickness of the parts to be welded, rods $\frac{1}{16}$ to $\frac{1}{8}$ in. in diameter usually being satisfactory for aircraft work. A flux is not necessary, but the edges to be welded and the welding rod should be clean.

In electric arc welding, either alternating or direct current and a carbon or steel electrode may be used, but direct current with the steel electrode is to be preferred, the work to be welded usually being made the positive terminal.

Satisfactory gas and arc welds of the usual aircraft construction steels are accomplished with a good grade of steel welding rod of the following composition: 0.06 per cent carbon; 0.15 per cent manganese; 0.04 per cent each of phosphorus and sulfur, and 0.08 per cent silicon (all maximum).

The straight carbon and chromium-vanadium structural steels which have been used in the manufacture of airplanes are readily welded but for several reasons are being replaced rapidly by chromium-molybdenum steel of the composition known as S. A. E. No. 4130X, one reason being its excellent welding properties and the high strength which can be developed by heat treatment. The welding of nickel steels should be avoided whenever possible because of the relatively inferior properties of welded joints thereof. As a rule, the practice of welding together unlike steels is to be discouraged because of the usual difficulty of suitably heat treating after welding to fully favor both steels.

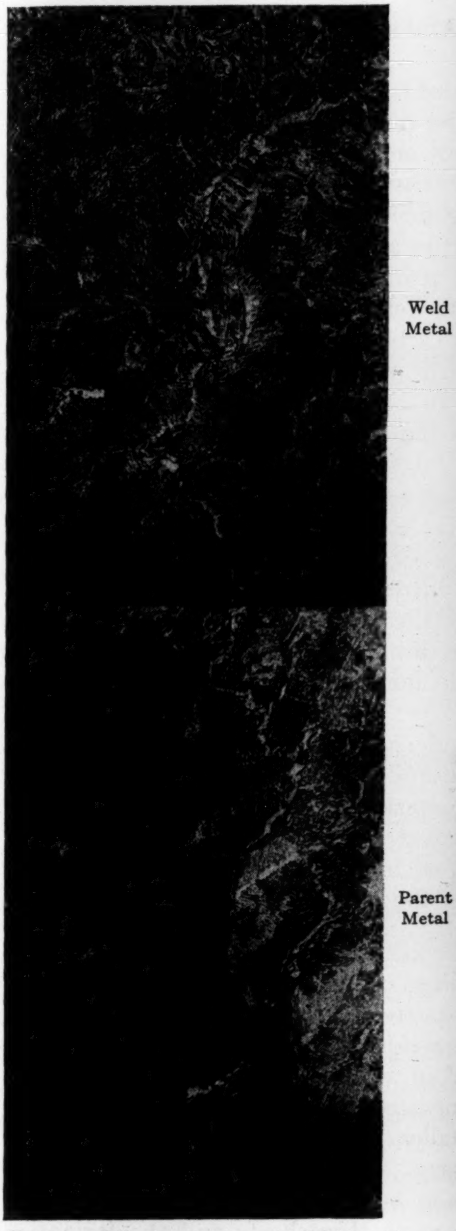

FIG. 1.—Microstructure at Weld of Alloy No. 4130X Chromium-Molybdenum Steel Tube Made With Low-Carbon Steel Welding Rod (× 100). Not Heat Treated.

Tensile Strength.—Parent metal (normalized), 95,000 lb. per sq. in., min.; weld, or adjacent metal, 80,000 lb. per sq. in., min.

Courtesy of Metallurgical Laboratories, Inc.

FIG. 2.—Same as Fig. 1, but Heat-Treated.

Tensile Strength.—Parent metal, 175,000 lb. per sq. in., min.; weld (not dressed), 140,000 lb. per sq. in., actual.

Courtesy of Metallurgical Laboratories, Inc.

Failure of untreated, undressed butt welds of good quality S. A. E. steel No. 4130X, using either low-carbon steel or parent metal as a welding rod, usually occurs about one-half inch from the weld, from 85,000 to 105,000 lb. per sq. in. tensile strength with an elongation in 2 in. of 3 to 7 per cent being developed in tension. Normalizing moderately improves the properties after welding. After heat treatment involving quenching and tempering, strengths up to 130,000 lb. per sq. in. in tension for butt welds of sheets and tubes 0.035 to 0.188 in. thick made with low-carbon rod, and up to 180,000 lb. per sq. in. for those made with parent metal, are reported by Johnson.[1] Welds made with low-carbon steel are in general more reliable and more uniform than those made with alloy steel and are therefore preferred.

A gas or an arc weld is in reality a casting but has better strength and a finer grain structure than the usual sand castings because of the difference in the conditions under which it is made. The coarse structure in and adjacent to an untreated weld of S. A. E. chromium-molybdenum steel No. 4130X made with low-carbon welding rod is shown in Fig. 1. The effect of heat treatment by quenching from above the critical temperature in refining the grain is apparent from Fig. 2.

Because of the physical and chemical differences which obtain between sections of the metal in and near a weld, joints of this type may, under certain conditions, constitute seats of serious corrosion. The danger of corrosion is greatest in untreated welds and is considerably reduced by any form of heat treatment in which heating above the critical temperature of the welded metal is done.

Aluminum Welding:

Aluminum and its strong alloys can be welded by the gas method in somewhat the same manner as steel, although, under certain conditions, cracking may occur in welds of duralumin unless adequate provision is made for the relief of stresses set up in cooling. Less heat is required than in welding steel because of the lower melting points and for this reason smaller torches can be used and more delicate manipulation is necessary. Both butt and flange welds of the wrought sheets can be made but the latter type is preferable because of its ease of application to thin sheets and the formation of a bead on the side of the sheet opposite the flame, which makes for a generally more satisfactory weld as regards appearance, properties and performance. In making butt welds a filler rod is necessary and may be either parent metal or an alloy of 5 per cent silicon and 95 per cent aluminum. The silicon rod has a lower melting point than the metal to be welded and is not hot short, which characteristics operate to reduce cracking at welds for which proper allowance has not been made for the relief of stresses set up in cooling. In making the flange type of weld, the edges to be joined are bent up at 90 deg., over a radius as small as can be used without cracking, to a height equal to about twice the thickness of the sheet. The flanges are placed back to back and "tacked" together at intervals with the flame. Flux is applied to the flanges which are then simply melted down with the addition of welding rod only where needed, which is usually very little. Oxyhydrogen is preferable to oxyacetylene provided sufficient heat to accomplish the work in hand is supplied by the flame. Tests have shown that cracking is less likely to occur in duralumin in complicated welds or at critical points with oxyhydrogen than with oxyacetylene. The powdered flux should be made into a thin paste with water and applied with a brush to the edges to be welded and the welding rod. It functions to dissolve the film of aluminum oxide which is always present on the metal and

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[1] J. B. Johnson. "Airplane Welding," p. 160.

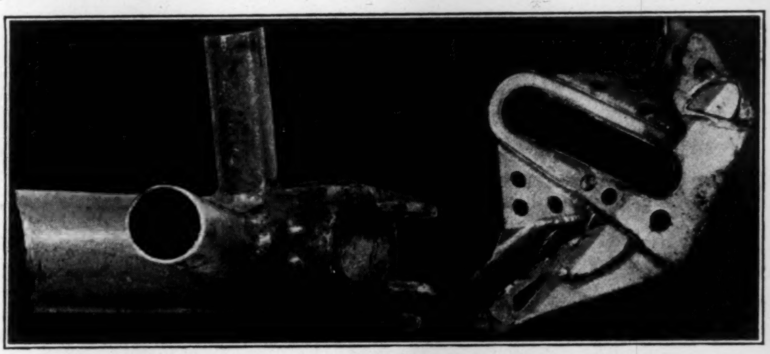

FIG. 3.—Welded Steel Fittings.

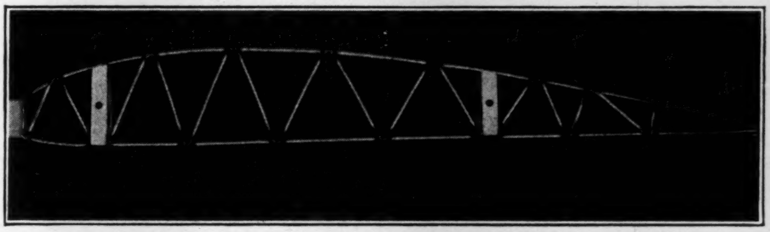

FIG. 4.—Stainless Steel Wing Rib Assembled by Spot Welding.

its alloys. A highly satisfactory flux is that of U. S. Navy Specification No. 51F2a. Its composition is as follows:

Sodium Chloride	32 per cent
Potassium Chloride	24 "
Lithium Chloride	24 "
Sodium Fluoride	20 "

After welding, all traces of remaining flux should be completely removed in order to preclude corrosion from this source. This may be accomplished by washing in a dilute solution (about 10 per cent) of sulfuric acid followed by thorough rinsing in water.

Heat treatment of duralumin after welding should be done for the double purpose of minimizing corrosion at the weld and improving its strength. Unless heat treated, corrosion will occur, apparently by electrolytic action, along a line parallel to and a short distance from the weld due to physical differences in the metal.

Welded aluminum sheet has a tensile strength of about 12,000 lb. per sq. in. Welded joints of the 1¼-per-cent manganese-aluminum alloy sheet from 0.032 to 0.051 in. in thickness develop a tensile strength of from 18,000 to 20,000 lb. per sq. in. with an elongation in 2 in. of 7 to 15 per cent. The following tension test values for undressed flange-welded joints of duralumin sheet made with the oxy-hydrogen flame are the average results of recent tests:

WELDING ROD	SHEET THICKNESS, IN.	YIELD POINT, LB. PER SQ. IN.	TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT
NOT HEAT TREATED; TESTED AS WELDED				
Duralumin	0.029	34 950	43 900	3.7
Duralumin	0.045	31 900	46 300	4.5
5-per-cent Silicon	0.029	33 350	47 150	6.5
5-per-cent Silicon	0.045	32 050	50 100	6.0
HEAT TREATED				
Duralumin	0.029	37 550	58 100	10.5
Duralumin	0.045	36 400	56 300	9.5
5-per-cent Silicon	0.029	37 400	60 800	15.2
5-per-cent Silicon	0.045	34 150	56 800	9.0

Electric spot welding of aluminum and its alloys may be done, but in order to obtain satisfactory results close control of conditions, particularly as regards current and pressure, is necessary. Good single-spot joints of aluminim have a strength up to about 250 lb. Results of tests on similar joints of duralumin sheet follow:

THICKNESS OF SHEET, IN.	BREAKING LOAD, LB.	
	AS WELDED	HEAT TREATED
0.014	136 to 216	155 to 320
0.029	336 to 580	545 to 705
0.045	512 to 810	805 to 1130
0.063	668 to 1079	415 to 1055

Applications of Welding:

In general, design of welded parts should be such as to avoid placing welds under heavy loads in direct tension or bending. Useful applications are made in compression and common shear. Various forms and combinations of welds of steel sheet and tubing are used in the manufacture of a variety of fittings, tubular construction of fuselages, wing ribs, ailerons, stabilizers, rudders, elevators, landing gears, engine mountings, tail skids, engine exhaust stacks, battery and seat supports and other miscellaneous parts. The "fish mouth" joint in tubes increases the length of the weld and is used extensively. Figure 3 illustrates the application of welding in making steel fittings. A stainless steel wing rib assembled entirely by spot welding is shown in Fig. 4. In the construction of aluminum gasoline, oil and water tanks welding is done in accomplishing the main joints and the heads of rivets are fused with the adjacent sheet with the welding torch to secure tightness. The flanges of pipe, strainer and sump fittings, etc., are also welded. Welded aluminum gasoline tank construction

FIG. 5.—Welded Aluminum Gasoline Tank.

is illustrated in Fig. 5. Welding of sheet duralumin is being done on cowling and in the production of wing-tip floats.

BRAZING

Brazing of steel parts is done by both the flame and dip methods. Flame brazing is identical in principle with dip brazing but is accomplished with the aid of the flame from a torch, the flux being applied usually in powdered form and the brass in the form of a wire. The surfaces to be joined are cleaned and held together by suitable means. The region of the joint is then heated with the flame, sufficient flux (usually a mixture of two parts borax and one part boric acid) added and melted to secure penetration between the edges or overlapping surfaces, and the brazing wire melted and allowed to run into the joint. Flame brazing should be done only where dip brazing is impracticable, as the latter method permits much better temperature control, avoids oxidation, and allows better opportunity for penetration of flux and brass.

Parts to be joined by brazing should first be cleaned of all oil, grease, paint, etc. This may be done in a hot solution of lye. Scale should then be removed by pickling, but not by sand blasting, as it has been found that sand-blasted surfaces interfere with the flow of the brass. Pinning, riveting, tack welding, spot welding, etc., may be used in holding together the parts to be brazed. Welding should be avoided whenever possible, but when used, any scale resulting therefrom on the surfaces to be joined should be removed as thoroughly as possible. Spot welds should not be made at vital points in an assembly, that is, in regions which may be highly stressed, as the metal is weakened and embrittled at such points and incipient cracks may be present, which might lead to failure of the part in service.

In dip brazing,[1] the parts are carefully preheated to a temperature of 800 to 1000° F. When uniformly heated they are transferred to the first flux pot, which is a clay-graphite crucible containing a mixture of two parts borax and one part boric acid held at 1300 to 1400° F. Sufficient time is allowed for the parts to reach this temperature. They are then removed and placed in a second flux pot similar to the first but held at 1600 to 1650° F. When this temperature is reached the parts are withdrawn and carefully lowered into a crucible containing the brazing brass, which is an alloy of 70 per cent copper and 30 per cent zinc covered by a layer of flux from 2 to 3 in. deep. (An 80-20 alloy has a somewhat higher melting point and may be used when there is danger of melting the brass or of the brazed parts separating in heat treatment subsequent to brazing.) Brazing with 70–30 brass is accomplished within the temperature range of 1830 to 1870° F. The production of a good joint is facilitated by raising the part several times through the flux covering the brass and lowering it again into the brass. After finally being allowed to remain in the brass several minutes the part is carefully withdrawn and cooled slowly to room temperature. This may be done by burying the part in lime or cooling in a furnace or chamber to 800 to 1000° F., after which natural cooling to room temperature may follow.

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[1] As developed at the Naval Aircraft Factory by H. C. Knerr.

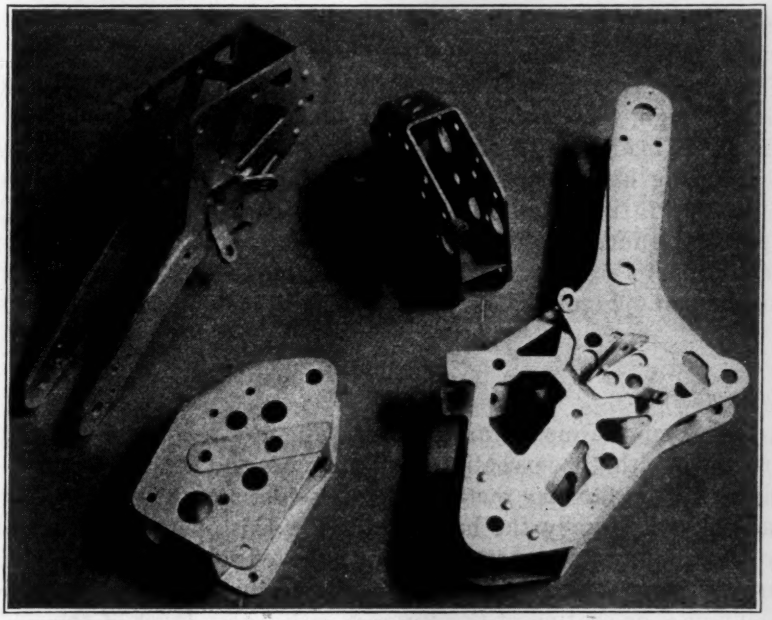

FIG. 6.—Brazed Steel Fittings.

Flux may be removed from brazed parts by immersion for a sufficient time in a boiling 15-per-cent solution of lye. Excess brass, except for lumps, is conveniently removed electrolytically by making the part the anode in a 10-per-cent water solution of commercial sodium nitrate, using about six volts.

Every precaution should be taken in brazing to avoid sudden temperature changes, as this is a positive source of cracking in fittings and other parts. At the fluxing and brazing temperatures the metal is weak and for this reason rough handling should be avoided. It is important that fluxing of surfaces to be joined be adequate and that the space between such surfaces be not excessive. The flow of the brass into joints should be by capillary attraction and it has been found that the best results are obtained with clearances of about 0.005 in.

Straight carbon, chromium-vanadium and chromium-molybdenum steels may be brazed satisfactorily, but more or less trouble has been reported with cracking in nickel steel. The effect of heat treatment on the strength of a brazed joint which fails in the brass is in doubt, but positive improvement in the properties of the steel which has been brazed may be effected by heat treatment.

Strengths up to about 36,000 lb. per sq. in. in pure shear are obtained in brazed joints, but 20,000 to 25,000 lb. per sq. in. is more nearly an average value and it is customary to use 10,000 lb. per sq. in. in design work. In resistance to corrosion the efficiency of brazed joints is high, there being no chance for the penetration of moisture into a well-made joint because of its tightness.

Brazing has its most extensive application in the manufacture of built-up fittings of sheet steel and in securing fixed and threaded types of terminals to strut ends. Reinforcing tubes and U-plates are brazed to steel struts, and washers, lugs, etc., are attached by this method. Figure 6 illustrates brazing in making steel fittings.

SOLDERING

Soft Soldering:

Most of the metals and alloys commonly used in aircraft construction, with the exception of aluminum and its alloys, may be joined by the familiar method of soft soldering with the usual tin-lead solders. Usually the heat required in this operation is supplied by a small, low-temperature flame or a heated soldering copper. The surfaces to be joined are cleaned mechanically and a flux is applied. "Tinning," or coating of the surfaces with a thin layer of the solder, is then done by heating and applying the solder. A joint is completed by placing and holding the "tinned" surfaces together and applying sufficient heat to melt the solder. "Dip" soldering is done by first cleaning the part, dipping in a suitable flux and then in the molten solder. Soldering is used on a great variety of parts where strength requirements and temperatures in service are low. On wrapped wire terminals, soldering serves simply to prevent movement of parts, the high stresses on the terminal being provided for otherwise. The most universally used soft solder contains about 49 to 50 per cent each of tin and lead, with antimony not over 0.25 per cent and copper not over 0.08 per cent. This grade begins to melt at about 360° F. and is completely liquid at about 415° F. Other grades of soft solder containing lead up to 70 per cent with correspondingly less tin, together with information regarding their melting and liquation points and special uses, are covered by U. S. Navy Specification No. 46S14.

Various soldering fluxes are used for different classes of work, zinc chloride made by completely neutralizing hydrochloric (muriatic) acid with zinc being probably the most universally useful. In addition to this, rosin, ammonium chloride, and a mixture of 15 per cent zinc chloride, 25 per cent glycerine and 60 per cent water are satisfactory for use on copper, brass, steel, terne plate, tinned steel, monel metal, etc. Hydrochloric acid is necessary on galvanized steel. The layer of solder in joints should be thin and after soldering all traces of flux should be removed by washing. If cleaning after soldering is thorough, soft soldered joints withstand ordinary corrosive influences quite satisfactorily.

A well-made soft-soldered joint will develop 5000 to 6000 lb. per sq. in. in shear; but loads much lower than these, if steadily applied, will cause failure of the joint for the reason that soft solder has a very low proportional limit, if any. Sudden application, with immediate release, of moderate loads under the breaking load, however, will not cause failure of the joint.

Silver Soldering:

Silver soldering is done with the aid of a torch, using borax or a borax - boric acid mixture for flux, in much the same way as flame brazing but at lower temperatures. These solders usually contain from 20 to 70 per cent of silver with 50 to 18 per cent of copper, zinc constituting the balance except for not over 0.50 per cent of tin and not over 0.20 per cent other impurities. U. S. Navy Specification No. 47S13a covers three grades of this solder.[1]

The melting points of silver solders vary according to the composition but are usually from 200 to 300° F. below those of the usual brazing brasses and about 1100 to 1200° F. above that of ordinary soft solder. This renders them useful in cases in which the soldered part is to be subjected to temperatures much above room temperature and where brazing is impossible or undesirable. In aircraft work, silver soldering has been limited to joining fittings to copper fuel and oil lines and to other miscellaneous special applications. Lap joints have a strength in shear up to about 35,000 lb. per sq. in.

Soldering Aluminum:

Most aluminum solders are zinc-tin-base alloys with or without certain percentages of aluminum, cadmium and copper.

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[1] See also paper by R. H. Leach on "Silver Solders," p. 493.—ED.

Because of the strongly electro-positive nature of aluminum, soldered joints thereof are subject to rapid disintegration in the presence of moisture due to galvanic action. If moisture is excluded, however, the condition of the joint will be unaffected by age. A solder consisting of 12 per cent silicon and 88 per cent aluminum is said to be quite resistant to electrolytic action but has the disadvantage of a high melting point, which is about 580° C. (1076° F.). Although soldered joints of aluminum may develop as much as 7000 lb. per sq. in. or somewhat more in tension when freshly made, the uncertainty as to their properties after exposure to atmospheric conditions prohibits their use for carrying appreciable stresses.

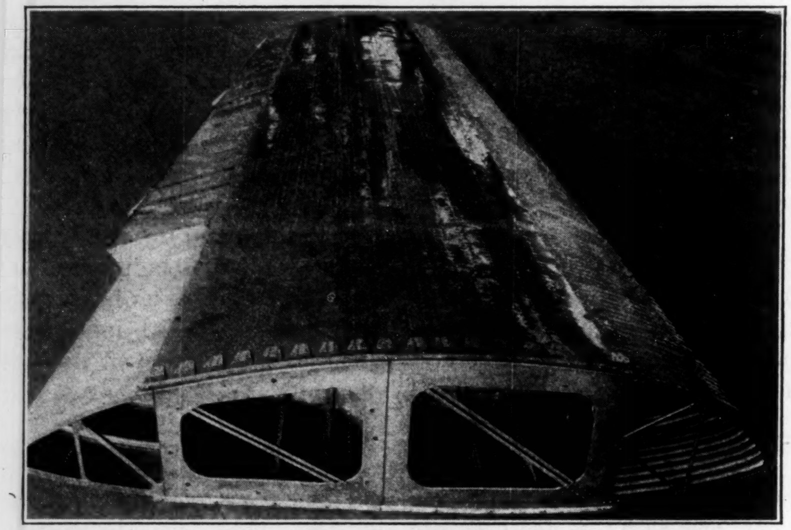

FIG. 7.—Riveted All-Metal Wing.

RIVETING

Rivets are driven by hand and with the pneumatic hammer and squeeze gun, the choice of method being governed usually by conditions at the joint, particularly accessibility. Cold heading must necessarily be done and rivets must be sufficiently ductile to preclude cracking in upsetting the point. Fortunately, the condition of duralumin is highly favorable to riveting for at least one-half hour after quenching from the heat treatment temperature, after which hardening and strengthening occur spontaneously upon aging at ordinary temperatures. Usually the same material is used in the rivet as in the metals to be joined.

The design and spacing of rivets in a joint is determined by the desired tightness and the load to be carried by each rivet in shear, the shearing strength for the material of the rivet being known and used in the calculation. Shearing strengths of 35,000 lb. per sq. in. for steel and 30,000 lb. per sq. in. for duralumin are used in design work. No strength requirement is placed upon aluminum rivets. Designs to place rivets in tension are avoided whenever possible.

Rivets are used practically throughout in the construction of duralumin floats and hulls and to a great extent in the construction of metal structural parts for wing panels such as wing beams and ribs. The method of riveting is also used in connecting fittings to struts. Riveted all-metal wing construction is shown in Fig. 7.

[For Discussion on Metal Joints, see page 206.—ED.]

PROCEDURE CONTROL IN AIRCRAFT WELDING[1]

BY H. L. WHITTEMORE,[2] JOHN J. CROWE[3] AND H. H. MOSS[4]

SYNOPSIS

Procedure control may be defined as a definite, detailed, particularized and complete statement of:

1. Specifications for the material and apparatus used,
2. Ability of the operator,
3. Technique used in each operation, and
4. Inspection of the finished product.

Aircraft welding in particular, as an art in which human skill plays an important part, is one in which procedure control can be used to insure uniformly good quality. In an investigation of the strength of welded aircraft joints conducted recently at the U. S. Bureau of Standards all specimens were welded under a procedure control prepared by the American Bureau of Welding. Included in the control were specifications for the apparatus used, tests of the base metal and welding rod for physical properties and weldability, tests to determine the ability and skill of the welder, and inspection of the welds. The quality of the work, as shown by the test results, was uniformly good.

It is believed, therefore, that procedure control, adapted by the manufacturer to his specific requirements, would, by reducing the human element to the absolute minimum, result in structures of consistently high quality.

The process of producing any commodity is always divided into two steps:

1. Design of the commodity in accordance with the requirements; and
2. Manufacture to the designer's specifications.

The problem of determining whether the finished product conforms to the designer's specifications and whether his assumptions have been realized is sometimes a simple one, but quite often requires a test of the finished product.

A simple visual inspection may be sufficient if the product is a metal ash tray, stamped by a die out of a piece of sheet metal. In the manufacture of bricks it may be sufficient to break several bricks out of each lot, in a testing machine, to see if they have the required strength. However, it may be impossible to test a concrete dam, and it must be assumed that its strength will meet the requirements.

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[1] Published with the approval of the Director of the Bureau of Standards of the U S. Department of Commerce, Washington, D. C.

[2] Chief, Engineering Mechanics Section, U. S Bureau of Standards, Washington, D. C

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[4] Engineer, Development Department, Linde Air Products Co., New York City.

In manufacturing processes in which human skill plays an important part procedure control has been used to assure uniformly good quality, especially when it is impractical or impossible to make a proof test.

In general, procedure control may be defined as a definite, detailed, particularized, and complete statement of:

1. Specifications for the material and apparatus used,
2. Ability of the operator,
3. Technique used in each operation,
4. Inspection of the finished product.

This definition is general and applies to procedure control for any purpose.

An illustration of what procedure control has accomplished in increasing the strength of concrete paving is given by E. A. Kemmler.[1] The compressive strength of cores cut from the concrete pavement is increased from 700 lb. per sq. in., in the case of no control and inadequate laboratory equipment, to more than 2500 lb. per sq. in. with good control. The change from fair to good control results in only a slight increase in the quality, as measured by the strength of the cores. Although it might be expected that procedure control would increase the cost, the data showed a gradual decrease in the cost from year to year.

Procedure control finds a particularly important application in industries using welding because the strength of welds depends on the human element. The strength of a welded joint depends upon skill much more than does the strength of a riveted joint. The weld must conform to predetermined dimensions as to the size of the bead, must have full penetration, uniform and complete fusion to the base metal, and must be sound, free from gas pockets or holes, fissures, plates of oxides, laps, or similar defects. If the weld is defective in any one of these particulars, failure in service may result, with risk to life and property.

Thousands of tests have established the fact that a weld properly made is a remarkably efficient method of joining metals. The old prejudice against welding, expressed, "You never know what you've got," was inspired by failure in unsound welds made by inexperienced operators or in cases where welding should not have been used.

The difficulty in testing a welded joint without destroying it emphasizes the need for control in making welds. Test specimens can sometimes be cut out of a joint and tested to determine the strength of the joint. This method is usually expensive, however, and not always practicable. Non-destructive methods of test have long been sought. The Sperry apparatus,[1] originally used for detecting transverse fissures in railroad rails, has been tried for welds with promising results, and testing with the stethoscope[2] has received much favorable comment. So far as is known, neither of these methods has been extensively tried out on welds in thin, tubular members.

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[1] E. A. Kemmler, "Concrete Paving—Base Control by Core Tests," ***Engineering News-Record,*** Vol. 100, No. 17, April 26, 1928, p. 660.

Probably no welded structure must meet such rigid requirements for strength as the airplane, due to low factors of safety and the disastrous consequences of failure. The designer has at his disposal various materials with certain properties. He knows by means of his stress analysis that if welded together in a certain way, they will carry the required load. His greatest problem is to be sure that his structure will have the computed strength. Procedure control for the welding gives him such assurance by reducing the human element in this process to the minimum.

In 1928 the U. S. Bureau of Standards started an investigation of the strength of welded joints in tubular members for aircraft. At this time there were no established rules of practice for aircraft welding which could be used as a standard of quality. It was considered of the utmost importance that all the welding done in this investigation be uniform and of good commercial quality, and it was realized that the test results would be of little value unless all factors affecting the strength of the joints were fixed and could be reproduced in commercial work. To insure these results it was decided that the welding be done under a procedure control especially prepared for aircraft welding.

Procedure Control for Gas Welding:

The American Bureau of Welding appointed a committee which prepared specifications for oxyacetylene welding in aircraft. The procedure specifications have been published[3] under the title, "Procedure Control for Welding Aircraft Joints." These specifications cover gas welding only. The procedure specification for electric welding has not been prepared.

Although prepared specifically for the welding of the test specimens in the Bureau of Standards investigation, they could be adapted with some modification and additions to the welding of aircraft in production.

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[1] E. A. Sperry, "Non-Destructive Testing of Welds," *Journal*, Am. Welding Soc., Vol. 8, No. 9, September, 1929, p. 48.

[2] A. B. Kinzel, C. O. Burgess and A. R. Lytle, "Non-Destructive Testing of Welds by Means of the Stethoscope and X-ray," *Journal*, Am. Welding Soc., Vol. 8, No. 9, September, 1929, p. 71.

[3] *Journal*, Am. Welding Soc., Vol. 7, No. 12, December, 1928, p. 40.

The procedure control specifies:

1. Requirements for the apparatus used, such as torches, regulators, hose, goggles, gases, etc.

2. Tests of the base metal for physical properties and weldability. The latter is determined by melting the tubing or plate with the torch on the surface and edge and observing its behavior. To be weldable the base metal should flow evenly and freely without boiling or giving evidence of gases, and should be relatively free of oxides, dirt, and laminations.

3. Welding-rod inspection, consisting of a surface flame test similar to that prescribed for the base metal and a weldability test in which the behavior of the rod during a welding operation is observed. The rod should flow freely and show evidence of being free from dirt or oxides.

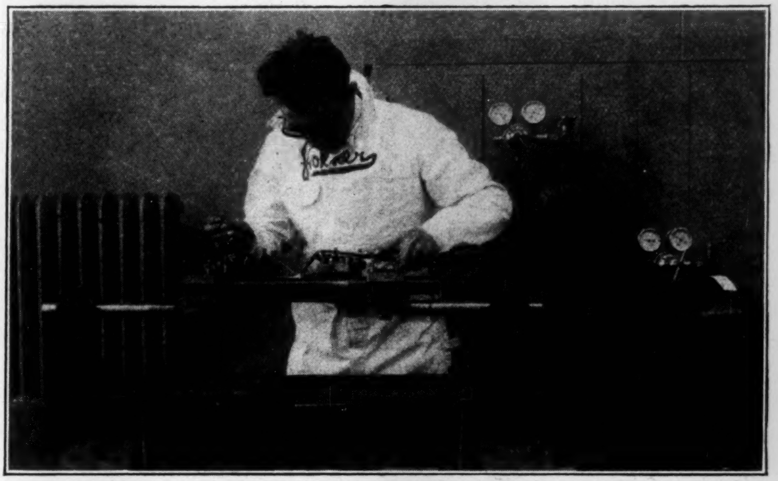

FIG. 1.—Welding an Aircraft Joint for Bureau of Standards Investigation.

4. Qualification of welders, consisting of several tests to determine the ability and skill of the welder. In the preliminary test, designed to eliminate unskilled men, the welder is required to make butt-welds in several positions, also to join materials differing widely in thickness. The supervisor inspects the welds for proper penetration and fusion, correct dimensions, etc.

If the welder passes the preliminary test satisfactorily, he is given the final qualification test which consists of three parts. He is first required to make butt-welds in both horizontal and vertical positions, some of which are tested in tension. If the joint breaks

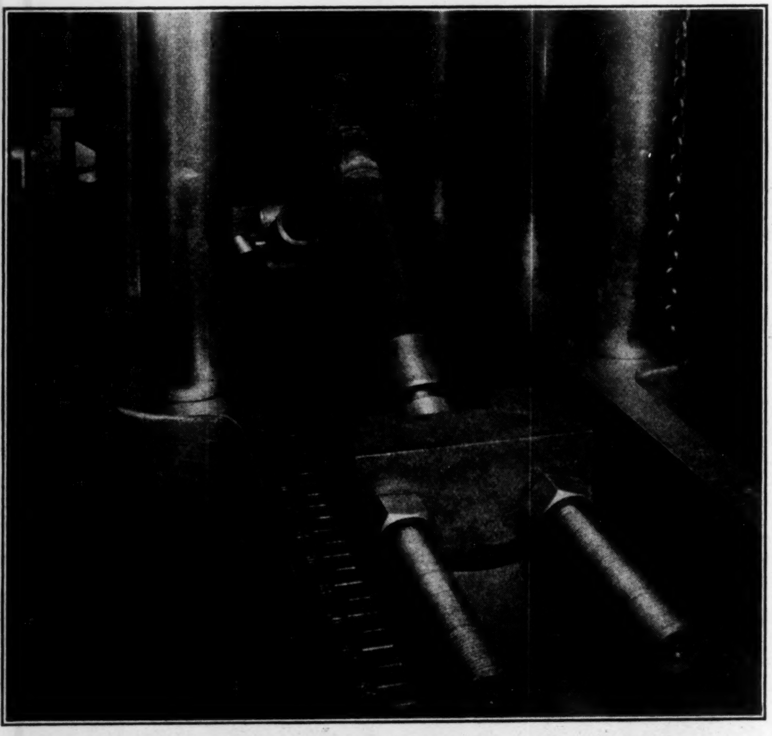

FIG. 2.—Testing a Joint Welded Under Procedure Control.

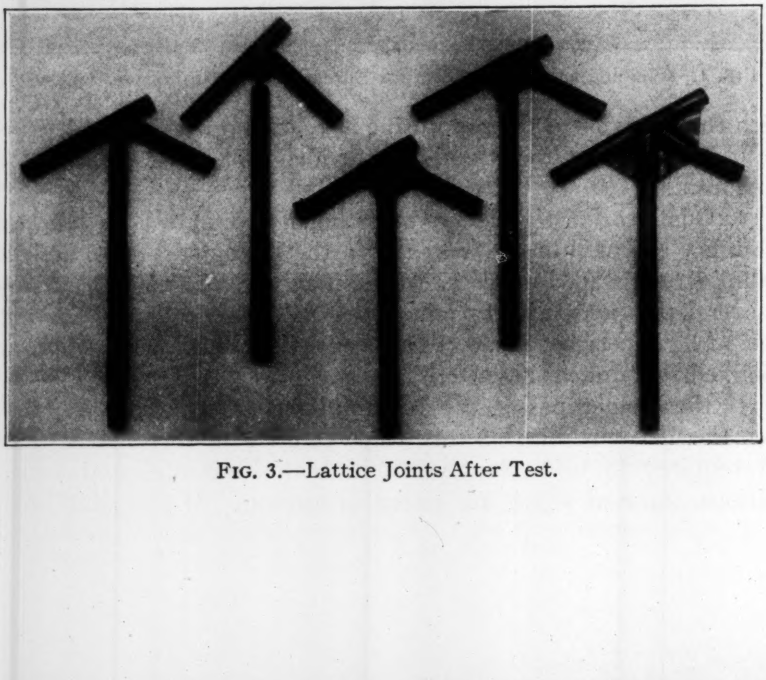

FIG. 3.—Lattice Joints After Test.

in the weld metal, the required strength is 50,000 lb. per sq. in. for mild-carbon tubing and 80,000 lb. per sq. in. for chromium-molybdenum tubing.

Other joints are tested for the ductility of the weld by flattening the joint in a vise or testing machine until the tube diameter is reduced by half. The weld must bend without cracking.

The welder is then required to weld joints in which plates are inserted in slots cut in the tubes. These joints are then sawed through the weld to determine fusion, penetration, etc.

5. Other items essential to a sound application of welding, such as gaging welds, use of welding jig, preparation of specimens for welding, etc.

In the Bureau's investigation the procedure control was carefully followed. The welding of the test specimens was all done by one welder who successfully passed the qualification test. Figure 1 shows a lattice joint being welded in the jig. Figure 2 shows a lattice joint being tested, and Fig. 3 shows several joints after test. A supervisor watched the making of the welds and approved those which were satisfactory. There were no rejections.

In this investigation the quality of the work was shown by the results of the tests. The test results show that the quality was uniformly good. Among the specimens in the investigation were a number of butt-welds in tubing. All of these passed the requirements of the qualification test, showing that it is a good index of the welder's ability in his daily work. In testing groups of three butt-welds made in the same tube, the strength of any one joint was in most cases found not to vary from the average for the three by more than 2 per cent although a different torch was used for each. Practically every joint broke in the tube about $\frac{1}{2}$ in. from the weld.

Procedure Control in Production:

A procedure control to be used in production would be a somewhat more detailed control than that used by the Bureau of Standards. In addition to the topics mentioned above, it would contain specifications for every major welding operation in the airplane.

It would contain minimum experience and training requirements for the welders and, in addition, detailed qualification tests consisting of an initial test when the welders are hired to prove the welder's ability and periodic rechecks at definite intervals to show that the welder is producing uniformly good welds.

It would specify the preparation to be given every joint prior to welding. The shape of the tube ends would be fixed. Directions for assembling the parts in the jigs would be included. Clearances between parts to be welded and allowances to be made for shrinkage would be fixed to minimize locked-up stresses which might cause warping and cracks. The location of each tack weld would be specified.

For the actual welding of the joint it would specify the torch, tip size, gas pressures, and size of welding wire to be used. It would fix the dimensions of the bead, giving the tolerances, and the order and direction of welding each seam.

It would be enforced by inspectors, say one for each five to ten welders, who would be responsible for seeing that every requirement was met and would be guided in their inspection by specific directions contained in the procedure. As little as possible would be left to the discretion of the welders or inspectors.

It would be prepared from information obtained by welding experimental structures and from published data, such as the Procedure Control of the American Bureau of Welding and "Airplane Welding,"[1] by J. B. Johnson.

The above description gives some idea of the scope of an efficient procedure control, although it does not cover all of the points which might be included. Many factors, seemingly insignificant, could better be specified in the procedure control than left to the discretion of the operator, and could much easier be decided in the drafting room than in the shop.

In this manner, by reducing the human element to the absolute minimum, structures of consistently high quality will result.

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[1] Goodheart-Willcox Co., Inc., Chicago, 1929.

[For Discussion on Metal Joints, see page 206.—ED.]

X-RAY TESTING OF AIRCRAFT MATERIALS

By Ancel St. John[1]

Knerr[2] has aptly said that in aircraft "every ounce of material must justify its existence or go." X-ray examination of aircraft materials is a valuable means of enforcing this dictum. Applied properly it aids the designer in distributing materials most effectively, and then assures the user that the material is present where it is supposed to be. Some typical examples of the use of X-ray examination for such purposes will be interesting.

During the World War the necessity of conserving every bit of fine timber available in England reinforced the effort to cut down the weight of the wood-frame aircraft then in use. This led to the development of the laminated or "box" structure for spars and the like. These presented many opportunities for hidden defects, due to improper design, faulty workmanship or defective material. X-ray examination disclosed such conditions as end-blocks split by screws, joints improperly glued, and struts containing knots or resin pockets. Where design was at fault it was corrected. Where workmanship was at fault the workmen were either trained to do things correctly or were eliminated from the plant. Defective timber was detected before fabricating. Many of the lessons learned at that time, particularly with respect to design, are still followed where wooden structures prevail.

Since the introduction of aluminum and other light-metal castings, X-ray examination has been a great aid. Systematic study of casting design and foundry technique has enabled manufacturers of light-alloy pistons, crankcases, cylinder heads, shock-absorber cylinders, propellers and the like to produce castings of distinctly superior quality. When required, routine X-ray inspection of each casting has enabled the user to satisfy himself of the soundness of the particular castings supplied to him. When assured by physical tests that the material used has the proper strength-weight characteristics and by the X-ray inspection that each part contains the proper amount of material properly distributed he has felt justified in using much lighter structures than he would otherwise consider permissible.

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[1] President, St. John X-ray Service Corp., New York City.

[2] H. C. Knerr, "Aircraft Metallurgy," *Aviation Engineering*, March, 1929.

In certain cases, such as aluminum alloy propellers, it has been customary to permit dynamic balancing by drilling and loading with lead, within certain specified limits. It is customary practice in some quarters to make sure by X-ray examination that these limits are not exceeded.

The quality of fabricated metal stock depends upon the quality of the original ingot and upon the character of the fabricating operations. An X-ray study of ingot manufacture has enabled the maker of light-metal alloys to assure the quality of his ingots. A further study of fabricating operations has shown him how to avoid internal rupture and the like. X-ray control of these operations results in uniformly high quality of the product.

Some X-ray studies of welding operations have been made. The results are encouraging. They show that excellent radiographs can be secured even with very complicated fuselage assemblies. For instance, in one case a group comprising five pieces of chromium-molybdenum steel tubing and two reinforcing plates formed a single assembly. In the radiograph the details of all the joints were shown, including a region near one joint where the tubing was unduly thin just adjacent to the edge of the weld metal and unduly thick slightly further away. This was undoubtedly the "puckering" which Backus[1] has commented on. In another region a crack was disclosed just outside the edge of the weld. This crack was not visible on the sand-blasted surface but was discovered on the inside when the tubing was sectioned.

The value of X-ray testing lies in its ability to thus disclose the existence, the location and the character of defects concealed from visual observation by overlying material, without alteration or damage to the object examined. This holds whatever the nature of the object. When the X-ray test is applied at the proper stage in manufacturing operations it not only assures the satisfactory quality of the final product, but frequently pays for itself by eliminating useless labor on material, say knotty timber or porous castings, which would otherwise be rejected when defects are brought to the surface at a later stage, and also by permitting the use of material which would otherwise be rejected on suspicion.

For aircraft, however, the question whether X-ray inspection pays for itself in these ways is much less important than the question whether it permits the use of lighter structures. This, in turn, is less important than the question whether the structures, whatever their design, contain the types of material they are supposed to contain distributed as it is supposed to be distributed. Wherever X-ray tests can furnish a satisfactory answer to this question, their use, in view of the risks to property and human life involved in a structural failure, would seem to be mandatory.

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[1] H. A. Backus, "Welding Experience Gained by One Aircraft Builder," *Airway Age*, June, 1929.

[For Discussion on Testing, see page 200.—ED.]

PHOTO-ELASTIC STUDIES OF AIRCRAFT PARTS

BY T. H. FROST[1]

SYNOPSIS

The photo-elastic method of stress analysis is briefly explained and a photograph of the apparatus used is shown. Stress determinations on several types of aircraft structures are discussed and the models used for the studies are shown by illustrations. The problems dicussed include the rigid airship Shenandoah, box girders for cantilever monoplane wings, airplane wing spars and the fuselage of a cabin passenger plane of monocoque construction.

The photo-elastic method is an experimental means, utilizing the temporary double refraction of transparent bodies when stressed, for the determination of the state of stress existing in engineering structures. In using this method a model of the actual structure is built of some transparent material, usually celluloid, and after being mounted in a suitable loading frame is placed in a beam of polarized light and subjected to load. In the unloaded condition the image of the structure, when analyzed and projected on a screen, shows as a very dark shadow but when loaded it becomes brilliantly colored at the stressed points. These color effects can be quantitatively analyzed and the directions as well as the magnitudes of the stresses determined with accuracy.

The photo-elastic apparatus, as used in the laboratories of the Massachusetts Institute of Technology, is shown in Fig. 1. The polarizing Nicol prism, *3*, is covered in the photograph by the screen, *4*. The analyzing Nicol, *9*, however, is clearly shown attached to the front of the camera, *10*. The model being investigated in this case consists of a small simple beam, *11*. The measuring device *12* used for the determination of the magnitudes of the stresses can also be seen. The various lenses shown in the figure are merely for securing proper focus of the model as well as the measuring device. In using the method the determinations are usually made from visual observation of the image on the screen shown directly behind the camera, but photographs in natural colors of the stress distribution are normally made for purposes of record. Figure 2 is a reproduction of a black and white print of a natural color photograph showing the stress distribution around a V-shaped notch in a member in tension.

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[1] Assistant Professor of Physics, Massachusetts Institute of Technology, Cambridge, Mass.

Considerable work has been done on the stress distribution in rigid airship frames of the zeppelin type. Figure 3 shows a three-quarter model of the airship Shenandoah which was constructed a few years ago for the Bureau of Aeronautics, Navy Department. The framework as well as the wiring has been duplicated as can be seen from the photograph. The girders in the actual ship were of triangular or rectangular latticework type while those used in the model are solid and rectangular. This departure was made to facilitate the use of the photo-elastic method and proved to be satisfactory for the purpose. The wires in the model could be tightened at will and a special tension meter of the Larsen type allowed the determination of the load

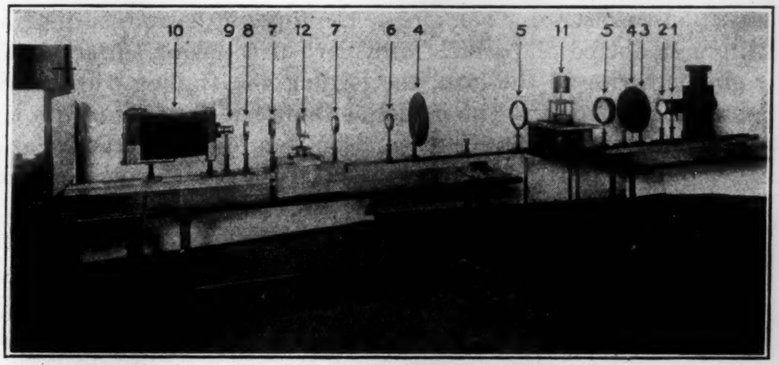

FIG. 1.—The Photo-Elastic Apparatus.

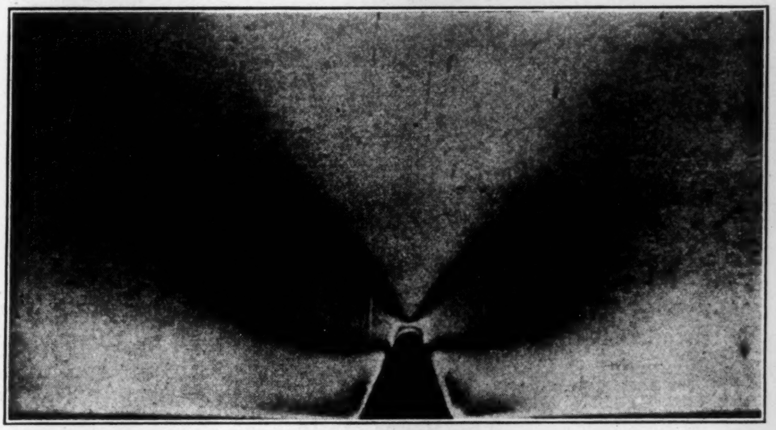

FIG. 2.—Showing Stress Distribution Around a V-Shaped Notch in a Member in Tension.

carried by each wire. The model was loaded for the tests in various ways to simulate the conditions which might be encountered in actual flight.

Figure 4 shows a model of a box girder in position to be subjected to torsional load. In several types of monoplanes, the cantilever wing construction consists of a box girder, the top and bottom surfaces of which are cambered and which form part of the wing surface itself. This girder carries all the load, the leading and trailing edges being of lighter construction. The model as shown in the photograph has not the cambered surfaces on top and bottom found in practice as it was thought best to start with a rectangular shape and work outward.

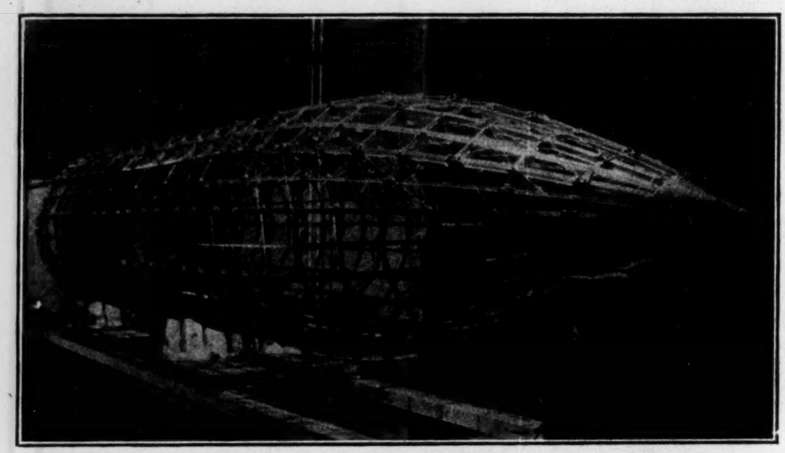

FIG. 3.—A Photo-Elastic Model of the Rigid Airship Shenandoah.

The five bays in the model as shown are separated by bulkheads which can be traced by the transverse lines of screws which fix them to the skin of the girder. The object of these first experiments was to determine the validity of the usual formulas for the calculation of the stresses in box girders. The Berry strain gage shown in the figure was used to determine the longitudinal deformation of the model when loaded, this measurement serving as a check on the photo-elastic determinations. After the tests on the model were completed it was altered by lightening the narrow sides of the rectangle, the solid sections being replaced by a Warren truss cut-out effect. In both cases, due to the very nature of the experiment, it was possible to check very closely on the accuracy of the work, the results being extremely satisfactory.

Further studies on airplane wing parts have been made using models of wing spars such as are normally found in commercial biplanes. These models consisted of thin I-beam sections which were considered as one-half of the small box spars used in actual practice. The object of the experiments was to determine the distribution of stress around the lightening cut-outs ordinarily placed in the webs of such beams. Both circular and Warren truss cut-out types were studied under a uniformly distributed cantilever load with interesting results.

Recently an examination has been made of the stresses in a side panel of the fuselage of a cabin passenger plane of monocoque construction. The perforations necessary for doors and windows in the fuselage of such aircraft constitute a real problem from the point of stress distribution and these experiments constitute the first step in a series of such investigations.

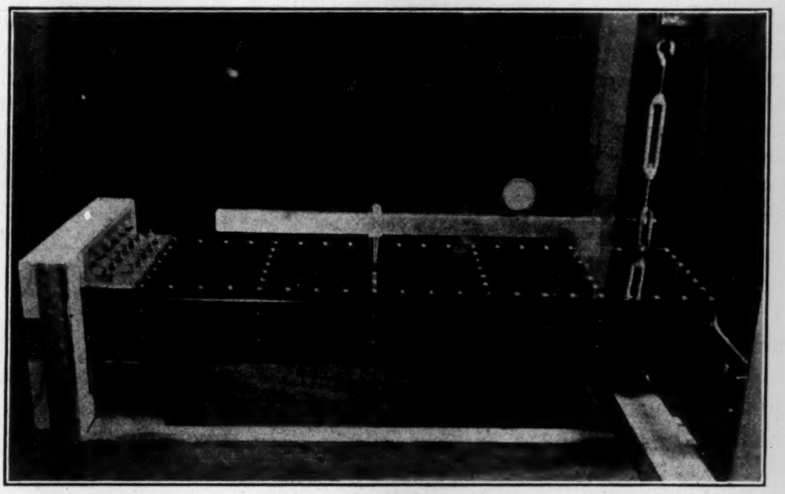

FIG. 4.—Test of a Box Girder Wing Spar.

Among other problems which have been attacked by the photoelastic method are the stresses in the landing gear of a military plane at the moment of landing and the distribution of stress in the flying deck of an airplane carrier. At the present time an investigation of the stresses carried by certain parts of an aircraft engine is under way.

[For Discussion on Testing, see page 200.—ED.]

HEAT TREATMENT OF AIRCRAFT PARTS

By Horace C. Knerr[1]

Synopsis

The paper discusses briefly the purposes of heat treatment and the effects thereof upon the mechanical properties of metals; the metals treated; the advantages, from the standpoint of design, inspection, storage and processing, of standardizing upon a minimum variety of alloys of specified composition; the processes of heat treatment for steels and aluminum alloys and the theory underlying them; the character of furnace equipment called for in the heat treatment of various types of aircraft and engine parts, means for control of furnace atmospheres and temperatures, quenching means, and the relation of these to the results obtained; metallurgical factors requiring technical direction and supervision, and precautions for insuring satisfactory and uniform results. Tables of heat treating data are presented. A list of references wherein more detailed information may be found is appended.

Purposes of Heat Treatment

The principal materials of construction for aircraft and aircraft engines are heat-treated metals.

The purpose and effect of heat treatment is to bring about certain improvements in the properties of the metal, including one or more of the following:

Strength,
Ductility,
Hardness or wear resistance,
Fatigue resistance,
Shock resistance (impact),
Corrosion resistance,
General reliability, and
Workability.

Strength and weight of materials of construction must be considered concurrently. Commercially pure aluminum is a "heavy" material because of its low strength. Alloy steels and aluminum alloys are light materials when their strength has been raised to maximum values by means of heat treatment. Materials may be compared on the basis of their strength-weight factors, as indicated in Table I.

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[1] Consulting Metallurgical Engineer; and President, Metallurgical Laboratories, Inc., Philadelphia, Pa.

Ductility is desirable as imparting the ability to withstand accidental and temporary overload (causing permanent deformation) without rupture. This is one of the important advantages of metals over wood for structural parts. A high combination of strength and ductility makes for toughness and is greatly influenced by heat-treating practice.

Hardness or wear resistance is called for principally in certain engine parts. Plain carbon or alloy steels of relatively high carbon content are employed where hardness throughout the thickness is desired or not objectionable. When a tough and ductile core is needed, steels of lower carbon content are used, and the surface of the finished part hardened by a process such as carburizing, cyaniding, or nitriding. Practice is similar to that in the automobile industry.

TABLE I.—TYPICAL STRENGTH-WEIGHT FACTORS OF AIRCRAFT MATERIALS.

Material	Strength, lb. per sq. in.	Specific Gravity	Strength-Weight Factor[a]
WROUGHT METALS (TENSION):			
Music wire, 0.01-in. in diameter	400 000	7.85	51
Alloy Steel (Heat Treated, High)	200 000	7.85	25
Alloy Steel (Heat Treated, Medium)	150 000	7.85	19
Duralumin	55 000	2.85	19
Magnesium Alloy	34 000	1.75	19
Alloy Steel (Normalized)	95 000	7.85	12.1
Mild Steel (Normalized)	55 000	7.85	7.0
Aluminum (Annealed)	12 000	2.7	4.4
WOOD (COMPRESSION):			
Balsa	2 200	0.12	18
Douglas Fir	6 000	0.54	11
Spruce	4 300	0.43	10
Oak, White	5 900	0.74	8

[a] Obtained by dividing ultimate strength in thousands of pounds per square inch, by specific gravity.

Fatigue resistance or endurance of metals under repeated or alternating stress ordinarily increases in proportion to tensile strength(**1**).[1] In this respect it is a function of heat treament. The endurance of a given part may be very much lower than calculated values because of notches, tool marks, "transverse grain," internal defects or inclusions in the metal, or other mechanical causes.

Shock resistance is the ability to withstand a blow or impact load. Like fatigue resistance, it is greatly affected by the direction of fiber of the part, and by sudden changes in section or by reentrant angles or notches. Low impact strength or brittleness is also produced in certain steels, ordinarily those containing chromium, by slow cooling from the tempering temperature. When the thickness is 1 in. or more, such steels should be quenched after tempering. Thin parts cool rapidly enough in air. Brittleness may also be caused by overheating prior to quenching, or by failure to temper properly after quenching.

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[1] The boldface numbers in parentheses refer to the papers given in the list of references appended hereto.

The resistance to corrosion of light aluminum alloys and of corrosion-resistant steels may be impaired or improved by variations in heat treatment.

When metals are cold formed or machined with heavy cuts, internal stresses remain. Hot forming and welding influence the internal structure of the metal. The resulting physical non-uniformities may impair the behavior of the material in service. A suitable final heat treatment is frequently the remedy and contributes to general reliability.

Prior to forming, machining or other mechanical operations an annealing treatment to improve workability may be called for.

MATERIALS TREATED

The term "heat treatment" as here used refers to metallic materials.[1] The metals treated include alloy steels and some plain carbon steels, and aluminum alloys, cast and wrought. These may be further classified under engine parts and structural parts.

Heat treating problems in aircraft production, as well as problems in the purchase, inspection, storage and identification of stock, and in engineering practice, are greatly simplified by standardizing upon the minimum number of metals and alloys which will adequately serve the diverse requirements. For structural parts, a very few steels and aluminum alloys have been found sufficient(2, 3). For engine parts a somewhat greater variety may be desirable, but the tendency may well be toward simplification rather than diversification(4, 5).

PROCESS

The heat treatment of metals to strengthen them consists fundamentally in heating to a certain temperature determined by the chemical composition, holding at this temperature long enough to permit thorough penetration (saturation) of heat and for such additional time as may be required to complete certain internal changes in the structure of the metal, followed by rapid cooling in a quenching medium. A second heating to a lower temperature is ordinarily applied; this is known as "tempering" in the case of steel and "aging" in the case of aluminum alloys.

In steels, the first heating or "quenching" temperature is slightly above the transformation temperature or crictical range of the metal. Two distinct types of internal changes take place: One is a recrystallization resulting from a rearrangement of the atoms from one type of space lattice to another. This is accompanied by grain refinement. The other is a taking into solid solution of hardening constituents, principally carbides (for example Fe_3C), which in the untreated steel are present in microscopic particles of relatively large size. Upon quenching, further grain refinement takes place, and the hardening constituents are retained in a very finely divided, sub-microscopic state, possibly in atomic dispersion. After quenching, steels are ordinarily harder than required, lack the desired ductility and may have internal stresses, which detract from their external strength.

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[1] Other forms of heat treatment are applied to wood in the dry kiln, to enamels in baking, etc.

FIG. 1.—Vertical Electric Furnace with Automatic Control for Heat Treating Aircraft Parts.

Tempering relieves the internal stresses, causes a slight increase in size of crystalline grains, a precipitation of atomically dispersed hardening constituents into minute particles and a growth of such particles into larger ones, the number thereof decreasing. These effects increase with the time and temperature of tempering.

Grain refinement and the presence of hardening particles of minimum size and maximum number contribute to hardness and strength. Increase in size of grains and of hardening particles results in softening, ordinarily accompanied by increased ductility.

If the temperature and time of heating prior to quenching are excessive, grain refinement is followed by grain growth, resulting in impairment of final physical properties, especially ductility and shock resistance. If temperature and time are insufficient, the desired recrystallization and solution will not be completed and maximum physical properties, especially strength, will not be obtained. If heating to the quenching temperature is too rapid or not uniform, warping, cracking and non-uniformity of properties may follow. Close and accurate regulation of heating operations is essential.

Aluminum alloys have no transformation point and there is no recrystallization. Hardening and increase of strength are due to the absorption (solid solution) of hardening constituents (consisting of chemical compounds of the aluminum and alloying elements present, as for example, $CuAl_2$, Mg_2Si, etc.) and the precipitation thereof in sub-microscopic particles after quenching. The solid solubility of these hardening constituents increases with temperature up to the incipient fusion point. In order to get maximum hardening and strengthening effect it is therefore necessary to heat to as near the temperature of incipient fusion as practicable before quenching. Exceeding this temperature causes permanent embrittlement of the metal. Little or no harm results from prolonging the time at the quenching temperature because serious grain growth does not occur.

Unlike steel, aluminum alloys are soft immediately after quenching. This is due to the absence of grain refinement such as occurs in steel upon quenching, and to the fact that the hardening constituents are retained in too finely divided a state to produce hardening, perhaps in atomic dispersion. Upon reheating to a moderate temperature, precipitation and particle growth of the hardening constituents takes place. In duralumin, normal atmospheric temperature is sufficient to cause precipitation of hardening particles. This hardening action therefore proceeds without special heating, rapidly at first, and then more gradually for about ten days. Hence the term "age hardening" or "aging." Certain aluminum alloys must be heated to produce the desired precipitation, with its accompanying strength and hardness, remaining soft until so heated. If the aging temperature is too high or, above certain limits, too prolonged, the hardening particles are increased in size and decreased in number so that a reduction in hardness and strength takes place(6, 7, 10).

The foregoing discussion outlines very briefly the theory underlying the hardening of metals. The actual process in each case must be determined after a detailed analysis of all factors involved, not only from the standpoint of metallurgical theory but also in the light of numerous practical considerations. The problem is too complex to be left in the hands of the "man at the fire." Skill, care, and practical judgment on the part of the heat treater are essential, but satisfactory and consistent results can be obtained only through the use of thoroughly detailed instruction sheets or process specifications prepared under experienced metallurgical direction, and supplemented with direct technical supervision by the metallurgist. Routine matters may and should be reduced to standard practice, but in the aircraft industry, problems of a special nature constantly arise which, although perhaps seemingly trivial, may have serious consequences if left to the untrained man.

TABLE II.—HEAT TREATING TEMPERATURES, WITH CORRESPONDING PHYSICAL PROPERTIES.
(From U. S. Army Spec. Reference (11))

Steel	Normalizing Temperature, deg. Fahr.	Annealing Temperature, deg. Fahr.	Hardening (Quenching) Temperature, deg. Fahr.	Quenching Medium	Tempering (or Drawing) Temperature, deg. Fahr.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness
S.A.E. No. 1035	....	1525 - 1575	1525 - 1575	Water	1000	103 000	70 000	25.0	63.0	200
					1100	100 000	65 000	30.0	66.0	195
					1200	95 000	60 000	32.0	68.0	180
S.A.E. No. 1045	....	1475 - 1525	1475 - 1525	Water	1000	115 000	80 000	20.0	55.0	230
					1100	110 000	75 000	23.0	58.00	215
					1200	100 000	70 000	25.0	60.00	200
S.A.E. No. 1095	....	1400 - 1450	1400 - 1450	Water	650	......	......	....	....	...
S.A.E. No. 2330	1550 - 1600^a	1250 - 1300	1475 - 1525	Oil...	600	220 000	130 000	11.0	40.0	460
					800	180 000	150 000	12.0	50.0	390
					1000	125 000	100 000	15.0	55.0	270
					1200	95 000	75 000	20.0	60.0	225
S.A.E. No. 3250	1500 - 1600^b	1225 - 1275	1425 - 1475	Oil...	400	260 000	150 000	8.0	38.0	540
					600	240 000	175 000	10.0	42.0	510
					800	230 000	190 000	12.0	46.0	460
					1000	175 000	150 000	14.0	50.0	380
					1200	130 000	105 000	18.0	57.0	260
S.A.E. No. 4130X	1600 - 1700^a	1250 - 1300	1600 - 1650	Water	400	230 000	110 000	5.0	....	^{c}
					600	205 000	125 000	6.0	....	...
					800	180 000	150 000	8.0	....	...
					1000	145 000	115 000	12.0	....	...
					1200	115 000	90 000	20.0	....	...
S.A.E. No. 6130	1600 - 1700^a	1250 - 1350	1600 - 1650	Oil...	400	220 000	110 000	2 - 10	....	^{c}
					600	200 000	125 000	2 - 10	....	...
					800	175 000	150 000	3 - 11	....	...
					1000	135 000	110 000	4 - 12	....	...
					1200	115 000	90 000	5 - 15	....	...
S.A.E. No. 6135	1600 - 1700^a	1250 - 1350	1575 - 1625	Oil...	400	250 000	130 000	12.5	43.0	460
					600	230 000	175 000	12.5	45.0	420
					800	200 000	175 000	12.0	48 0	400
					1000	150 000	115 000	15.0	50 0	350
					1200	120 000	95 000	20.0	55.0	240
S.A.E. No. 6195	1650 - 1750^b	1250 - 1350	1425 - 1475	Oil.....	350	......	......	....	....	...

[a] Cooled in still air.
[b] Cooled in furnace.
[c] No data given.

METHOD

The exact method of heat treatment will be determined by the chemical composition of the metal, the size and form of the parts, the physical properties required, and the equipment available. For example, heavy steel forgings will not be handled in the same way as thin sheet metal fittings, while bulky or long and slender members such as undercarriages, engine mounts and wing beams require highly specialized heat treating equipment. Aluminum-alloy castings must be handled in a very different way than forgings, although the chemical composition may be nearly the same. The method and equipment for heat treating aluminum-alloy sheet and strip will depend upon whether members are to be formed in the soft state immediately after quenching or treated as a final operation.

TABLE III.—HEAT TREATING TEMPERATURES WITH CORRESPONDING PHYSICAL PROPERTIES.

(From Naval Aircraft Factory Heat Treatment Specifications)

Steel	Quenching Temperature, deg. Fahr.	Quenching Medium	Tempering Temperature, deg. Fahr.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Brinell Hardness		Rockwell Hardness, "C" Scale
						After Quenching	After Tempering	
S.A.E. No. 1025...	1615 - 1635	Air (Free)	None	55 000	36 000			
S.A.E. No. 1035...	1530 - 1570	Oil	950 - 975	80 000	60 000			
S.A.E. No. 1095...	1425 - 1450	Oil	590 - 610					
S.A.E. No. 2330...	1460 - 1480	Oil	800 900 1000	125 000	.....	425 - 475 475 - 525 525 - 575	250 - 300	....
S.A.E. No. 4130X..	1575 - 1600	Oil	1075	125 000	105 000		258 - 296	27 - 32
			925	150 000	125 000		296 - 340	32 - 37
			775	175 000	140 000		340 - 392	37 - 42
			600	200 000	150 000		392 - 436	42 - 46
S.A.E. No. 6130...	1600 - 1625	Oil	800 850 900	150 000	.....	300 - 350 350 - 400 400 - 475	300 - 350	....

NOTE.—The values given in Tables II and III are reproduced from the references without endorsement by the author. Considerable difference of opinion and experience exists with regard to heat-treating data, especially tempering temperatures and the resulting physical properties, for these steels.

Specifications for each kind of material and for each type of parts should be prepared covering in fairly complete detail all phases of the heat-treating process(8).

Variations of composition within the specified chemical tolerance of standard S. A. E. steels, as well as variations in thickness may cause pronounced differences in the hardness after quenching of parts made from a given steel. Such irregularities may be overcome by suitably varying the tempering temperature, hardness tests being applied after quenching, and the tempering temperature fixed accordingly, the correct values having been previously determined by experiment. Final hardness tests should be applied, preferably to all pieces, after heat treatment, to insure that they have responded properly. This practice has been followed at the Naval Aircraft Factory (Table III).

For steels, the quenching temperature will depend almost entirely upon the chemical composition, while the tempering temperature will be determined not only by the composition but also by the combination of strength or hardness and ductility desired, by the hardness of the part after quenching and the quenching medium employed. The difficulty of specifying tempering temperature is therefore considerable. Results are best arrived at by trial under given conditions of operation.

Quenching temperatures for aircraft parts should preferably be held within closer limits than is the practice of the automobile industry (as exemplified by the S. A. E. handbook). A tolerance of plus or minus 10 or 15° F. is desirable and practicable. To actually come within these tolerances requires that pyrometers and furnaces be of the best and that they be frequently checked. Close control of heat treating practice is repaid by exceptionally high and uniform properties in the product.

For aluminum alloys, the quenching temperature and also the tempering or aging temperature are determined by the chemical composition or type analysis of the alloy. For the best physical properties, it is desirable to work as close to the upper limit of quenching temperature as may be done without danger of accidentally exceeding it. Here, again accurate control is at a premium.

Heat treating temperatures for steels, as recommended by the Army and Navy, respectively, are given in Tables II and III. In the author's experience, better results have been obtained from the practice indicated below for chromium-molybdenum steel No. 4130X than from that indicated in Tables II and III:

PRACTICE IN HEAT TREATING CHROMIUM-MOLYBDENUM STEEL AIRCRAFT PARTS AT METALLURGICAL LABORATORIES, INC.

Normalizing Temperature	1575–1625° F. Cool in air.
Annealing Temperature	1275–1325° F. Cool in air, or 1375–1425° F. Cool in furnace.
Hardening (Quenching) Temperature	1575–1625° F. Quench in oil.

TEMPERING TEMPERATURE, DEG. FAHR.	TENSILE STRENGTH (MINIMUM), LB. PER SQ. IN.	YIELD POINT (MINIMUM), LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT*
680	200 000	180 000	5 to 7
775	175 000	160 000	7 to 9
940	150 000	135 000	9 to 11
1100	125 000	110 000	11 to 15

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[*] Yield point taken by divider method. Elongation values are greatly affected by thickness of test specimen. The values given are for tubes having a wall thickness not less than $\frac{1}{8}$ in. The influence of mass on the properties of strip test specimens simultaneously heat treated with tubes from which they were cut, is not great.

It should also be noted that differences exist between the data given in the specifications of the Army and the Navy. Such discrepancies are not unusual and may result from variations in the character of material tested, variations in methods of making tests, variations in heat-treating practice, etc. The relations between such variables as quenching temperature, tempering temperature, tensile strength, yield point, Brinell hardness, and Rockwell hardness usually vary between rather broad limits. Figures such as those given should be taken as a general guide rather than as fixed values.

Data and instructions for heat treating aluminum alloys are given in references (3) and (7).

EQUIPMENT

The character of the equipment required for heat treating aircraft parts will take various forms according to the subclassifications given below:

STEEL ENGINE PARTS:
- Heat treated before machining, and
- Heat treated after machining.

STEEL STRUCTURAL PARTS:
- Fittings and other small parts,
- Bulky members, and
- Slender straight members.

ALUMINUM ALLOYS:
- Castings,
- Forgings,
- Sheet, strip, etc., heat treated before final forming, and
- Bulky members heat treated after forming.

While it may frequently be possible to heat treat parts of one classification, for example, aluminum alloy forgings, in equipment intended for another, such as steel fittings or engine parts, such an arrangement will be in the nature of a compromise. The most efficient plan, where the quantity of work warrants, will call for distinct furnace equipment for each of the nine classifications above named. These will be considered individually.

Steel Engine Parts Heat Treated Before Machining.—These consist of drop forgings and bar stock. Certain alloy steels, such as chromium-vanadium and chromium-molybdenum, may be machined after having been heat treated to a strength as high as 150,000 or even 175,000 lb. per sq. in. Moderate deformation in heat treatment is not harmful, as it is removed in machining. Well-regulated oil-fired heat-treating furnaces are satisfactory, surface finish being unimportant. Heat treatment is ordinarily done in the drop forging plant rather than by the engine manufacturer.

Steel Engine Parts Heat Treated After Machining.—Such parts comprise those requiring high surface hardness, as gears, or other parts calling for a hardness too great for machining. Case-hardened work is included. The very closest control of temperature and atmosphere is necessary. Gas-fired furnaces having automatic regulation of atmosphere as well as of temperature are ordinarily preferable.

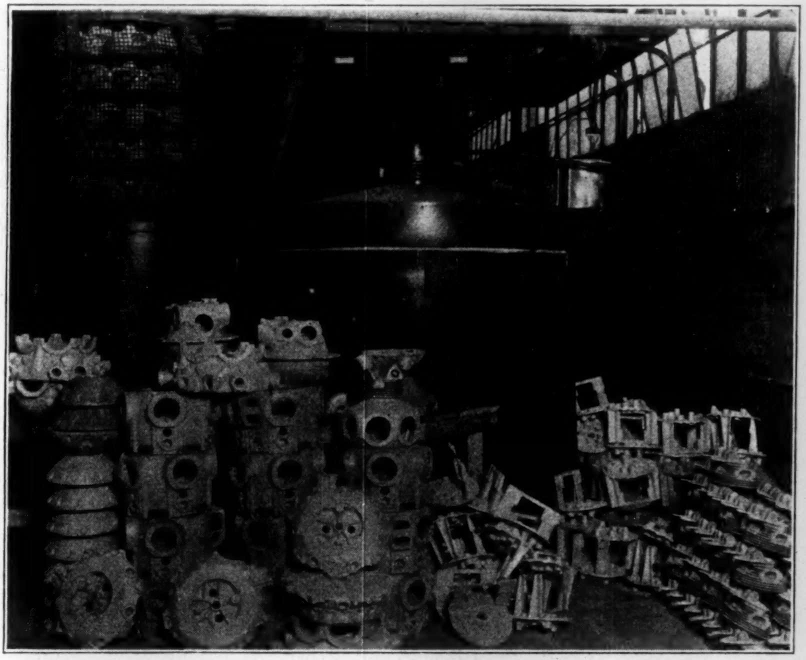

FIG. 2.—Furnace and Typical Castings and Method of Supporting Parts to Insure Uniformity and Avoid Distortion.

The heat treatment of steel engine parts for aircraft is similar to that for automobiles, and therefore does not require extended comment.

Steel Fittings for Structure.—These are, as a rule, made of sheet steel, tubing, etc., assembled by welding or brazing. They are thin, complex in form and delicate and must be handled with care to avoid distortion. Small, oil-fired, gas-fired and electric furnaces all have been used with success. Scaling and decarburization must be avoided, since even a moderate surface attack represents a large proportion of the total thickness and therefore of the strength. Surfaces are usually cleaned after heat treatment by pickling or by blasting with sand or steel grit. Small forgings and screw machine parts may be heat treated in the same equipment.

Structural Parts—Bulky Members.—Bulky members include such parts as engine mounts, sections of fuselage, control surfaces, V-type axles and undercarriage structures. These occupy a large volume in proportion to their weight. They are exceedingly delicate and if laid on the hearth of an ordinary heat-treating furnace are likely to sag at hardening temperatures under their own weight. Further distortion will occur when the work is lifted from the hearth to convey it to the quenching bath. When it is quenched, warping may result if the work enters the bath sidewise. Fixtures may be constructed to support the work during treatment but this adds to the complications of handling and increases costs. Because of their thin section, aircraft parts must be moved from the heating chamber to the quenching bath very quickly to prevent premature and non-uniform cooling in air.

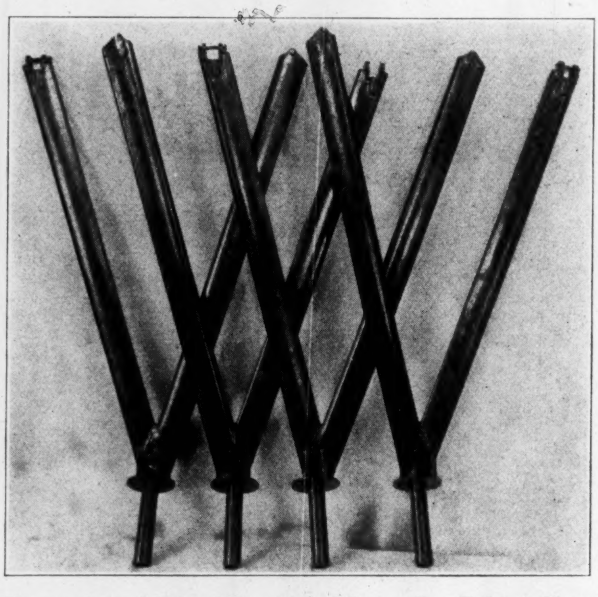

FIG. 3.—V-type Axles Made of Round and Streamline Tubing, Heat Treated After Assembly.

In the author's experience, the only satisfactory means of heat treating such parts consists of a vertical furnace mechanism like that described in the following section for slender straight members, but of suitable proportions.

Structural Parts—Slender, Straight Members.—As with bulky members, there are at least three chances for deformation when it is attempted to heat treat slender straight members in ordinary furnaces and quench tanks: First, sagging when the work is heated, second, bending when it is lifted from the furnace, and third, warping due to sidewise contact of the quenching medium. Very little straightening can be done on tubular parts of thin wall after heat treating to high strength. The difficulties increase rapidly with the length of the members.

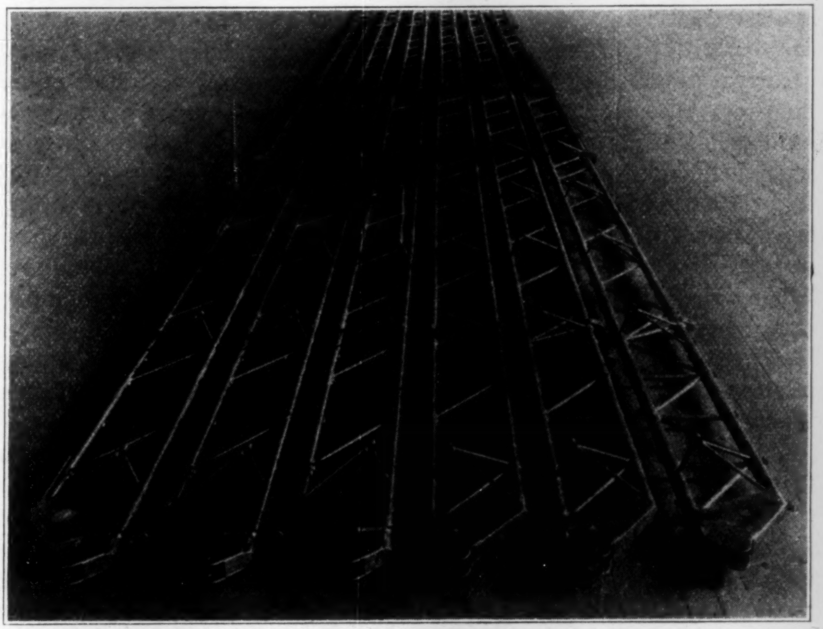

FIG. 4.—Alloy Steel Wing Beams 24 ft. Long, Made of Seamless Tubing, Joined by Welding and Heat Treated Without Distortion.

Parts coming under this classification include straight and bent axles, struts, wing beams or other spars, and tubing in round, streamline, elliptical, square and special sections as it comes from the tube mill. It is impracticable to heat treat such parts with ordinary equipment. Heat treating machines have been developed especially for the purpose(9). These embody a vertical furnace, electrically heated, with a door at its bottom, a vertical quench tank movable laterally beneath the furnace, and mechanism for drawing the work up inside the furnace, holding it freely suspended in the heating chamber and lowering it straight down into the quenching tank when ready. Before raising into the furnace, the charge is suspended from a spider of heat-resisting alloy in such a way as to be free of all tendency to sag under its own weight. It remains hanging on this spider during heating and quenching. After quenching, the tank is moved to one side and the spider and charge raised out of the tank and allowed to drain. The same equipment is used for tempering operations, except that quenching is omitted, the work being cooled in air. One machine has a heating chamber and quenching tank large enough to accommodate bulky members not over 10 ft. long (high) and 33 in. square, and another 25 ft. long and 2 ft. in diameter. These heat-treating machines are costly to build, to maintain and to operate. Their daily capacity greatly exceeds the requirements of even the largest aircraft manufacturer. It is therefore more economical for the aircraft builder to send such work to a central plant for treatment than to install his own machines.

Cast Aluminum-Alloy Parts.—Cast aluminum-alloy parts of high strength may readily be machined after heat treatment, and are therefore usually furnished by the foundry in the heat-treated condition. When the consumption is sufficiently large to justify the manufacturer in maintaining his own foundry, as is the case with certain engine builders, heat treatment may be done either before or after machining, as preferred, but in the latter case, allowances for possible deformation and growth may be necessary.

Cast aluminum alloys are heat treated principally in electric furnaces, usually of the pit type. The treating temperature is relatively low, the charge is bulky and the time is long. The parts are soft and tender at heat-treating temperature and must therefore not be piled. They may be placed in layers on flat steel baskets independently supported. The entire basket is removed with its charge for quenching, which is done in water. Aging may be performed in the same furnace, or in some cases, in other furnaces heated by steam. To promote uniformity of temperature and reduce the time required to insure that the charge has reached the desired temperature throughout, a fan or blower for circulating the air within the furnace chamber is desirable. Molten salt baths are not satisfactory for heating aluminum-alloy castings because the latter are sometimes porous and absorb the salts, with harmful results.

Aluminum-Alloy Forgings.—Forgings may be heat treated in ordinary furnaces, but because of the low temperature, the rate of heating is slow. A salt bath consisting of molten sodium nitrate may be used. The container for the bath may be of pressed or welded steel, heated with electricity, gas or oil. Various precautions should be observed (7). Quenching in water removes the adhering layer of salts (10).

Aluminum-Alloy Sheet, Strip, etc., Heat Treated Before Final Forming.—Channel sections, wing coverings and the like, made of sheet or strip, may be coiled, heated in a salt pot of comparatively small size, quenched in water and rinsed until all salts are removed, uncoiled and formed into the desired shape immediately while still soft and then allowed to age naturally. Rivets may be heated in small steel tubes, closed at the lower end, and lowered into the salt bath. This insures quick heating, keeps sizes separate, and avoids troubles due to salt adhering to the rivets. They are then dumped into small wire baskets in the water bath, drained and taken at once to the shop for driving. Unused rivets are retreated at the end of one-half to three-quarters of an hour to keep them soft.

Bulky Members, Heat Treated After Forming.—The softness of aluminum alloys at the heat-treating temperature renders them very liable to distortion. They may be straightened while in the soft condition but this entails much labor and the results are not always satisfactory. Heating such parts in a salt bath usually results in severe distortion during the effort of lifting them out of the bath. It is therefore better to heat them in an electric oven furnace, suspended from a rack or spider by means of iron wire at points sufficiently numerous to prevent sagging. The furnace atmosphere should be circulated to insure temperature uniformity and reasonably rapid heating.

Temperature and Atmospheric Control:

Recording pyrometers are preferable in connection with all aircraft heat-treating work. These provide a visible and permanent record of the rate of heating, the time held at temperature and the cycles of operation of the furnace. This assists the heat treater in his work and facilitates supervision thereof by the metallurgist and shop executive. Automatic control of temperature is frequently desirable, especially when operating temperatures are constant, as in the treatment of aluminum alloys, and in large furnaces which are divided into separate heating zones. In the latter case, each zone has its individual control instrument. When control is automatic, a recording pyrometer, with entirely independent thermocouples and lines, is desirable, as it affords a check in case either the recorder or controller gets out of adjustment.

In gas-fired furnaces automatic regulation of the air-gas mixture is desirable and economical and minimizes danger of scaling and decarburization.

Fusible links, arranged to shut off the supply of fuel or electricity in case the furnace temperature for any reason "runs away," are a valuable and inexpensive insurance against the loss of a charge and the production time to replace it.

Quenching:

For steel, a good commercial quenching oil is considered preferable to water wherever it can be used. Parts requiring a very hard surface usually call for water quenching. For strength members, either in engines or aircraft structures, oil produces less distortion than water and usually affords a better combination of strength, yield point and ductility.

For aluminum alloys, water is ordinarily employed as quenching medium. When the parts have been heated in molten salts, the water dissolves and washes off the latter. It has been found that the susceptibility to corrosion of duralumin varies with the speed of cooling during quenching, resistance to corrosion being best when quenching is rapid(10). From this standpoint, cold water is preferable. Water, especially when cold, distorts aluminum alloys much more severely than oil, whereas the physical properties resulting do not differ greatly. Oil is therefore to be preferred when the work is not heated in salts, and when absence of deformation is more important than maximum resistance to corrosion.

Certain bulky structures such as welded fuel tanks, will not permit of being quenched in a bath. Cooling in air, with the aid of electric fans, and a hose carrying compressed air to the inside, has given good results(5).

DIRECTION AND SUPERVISION

One-hundred-per-cent dependability is expected of aircraft parts. A single defective member among the thousands which comprise the engine and structure may cause disaster. Materials, processes and inspection must therefore be such as to insure that each individual part fully meets its designated requirements. Heat treatment is only one of a series of interdependent factors which determine the properties of metal parts and their reliability in service. Competent metallurgical supervision should be exercised over all these factors if satisfactory results are to be assured in the finished product. Such factors may be classified as follows(5):

A. Choice of materials and their correct use in design.
B. Specifications for purchase.
C. Inspection and test of raw materials.

D. Storage and indentification of stock.
E. Fabrication:
  1. Machining, punching, etc.
  2. Forming, hot or cold.
  3. Joining:

    (*a*) Rivetting,
    (*b*) Welding,
    (*c*) Brazing,
    (*d*) Soldering.

  4. Foundry practice.
  5. Heat treatment.
  6. Corrosion protection.

F. Inspection during fabrication.
G. Study of failures and defects to determine cause and prevent recurrence.
H. Investigation of new materials and processes, to determine fitness for aircraft use.

It has been demonstrated(8) that observation of the following precautions prior to, during, and subsequent to heat treating operations will insure the dependability of all metal parts and (aside from dimensional errors in machining, etc.) reduce rejections in final inspection to an almost negligible point:

1. Purchase of metallic materials under adequate specifications, which shall include among other things, chemical tolerance ranges as well as required physical properties.

2. Standardization upon a minimum variety of steels, aluminum alloys and other metals, and upon a minimum variety of physical properties in which each may be received, treated or used.

3. Restriction of each grade of steel to type analysis corresponding with a standard S.A.E. or Army-Navy steel number or the equivalent.

4. Rigorous inspection and test of raw materials to insure that specifications are met and that quality is uniform.

5. Clear and correct indentification of each piece of stock in storage and during processing.

6. Detailed process specifications covering the heat treatment of each type of material.

7. Reliable recording pyrometric equipment, frequently checked.

8. Properly designed and operated furnace and quenching equipment.

9. Hardness tests of steel parts after quenching, to determine correct tempering temperature and of all metallic parts following heat treatment to insure that they have responded correctly.

10. Intelligence, care and conscientious attention to instructions on the part of the heat treater.

11. Active technical supervision by a competent metallurgist of heat treating operations and of other processes which may influence the properties of metal parts and immediate investigation of any failures to determine their cause and prevent their recurrence.

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(3) R. L. Templin, F. V. Hartman and E. C. Hartmann, "Structural and Engineering Light Alloys for Aircraft," see preprint pamphlet of Symposium on Aircraft Materials to be held at the Thirty-third Annual Meeting of the American Society for Testing Materials, in June, 1930.

(4) R. R. Moore, "Materials of Construction in Aircraft Engines," see preprint pamphlet of Symposium on Aircraft Materials to be held at the Thirty-third Annual Meeting of the American Society for Testing Materials, in June, 1930.

(5) H. C. Knerr, "Aircraft Metallurgy," *Transactions*, Am. Soc. Steel Treating, Vol. XIII, No. 5, May, 1928, p. 723.

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(8) H. C. Knerr, "Steel Structural Parts for Aircraft," *The Iron Age*, September 27, 1923, p. 816.

(9) H. C. Knerr, "Heat Treating Aircraft Parts," *The Iron Age*, August 29, 1929, p. 519.

(10) H. C. Knerr, "Duralumin, a Digest of Information," *Transactions*, Am. Soc. Steel Treating, Vol. III, No. 1, October, 1922, p. 13.

(11) U. S. Army Spec. No. 98-10025, Heat Treatment of Certain Steel Parts for Aircraft.

[For Discussion on Heat Treatment, see p. 212.—ED.]

DISCUSSION ON AIRCRAFT MATERIALS

STRUCTURAL METALS

MR. R. L. TEMPLIN.[1]—Nothing was said in our paper on Structural and Engineering Light Alloys about the question of fastening these materials, such as riveting, but this has been mentioned in two or three other places in the symposium. In all such instances it has been recommended that the rivets be heated either in an air furnace or salt bath, whereas very good results have been obtained by using a lead bath. The quenching of such material in cold water of course is heartily recommended.

MR. BRADLEY STOUGHTON.[2]—I have seen it published that between 50 and 60 per cent of the engine parts of airplanes are made of aluminum and aluminum alloys. I should like very much to ask Mr. Templin if he would give us some more data on that point. I should also like to know what parts are made of these alloys. Also I notice Mr. Strauss said that the 18 per cent chromium, 8 per cent nickel type combinations were the most important ferrous alloys used in airplane construction. I am not sure that I understood rightly. I wanted to ask if he spoke advisedly in comparing that with the chromium-molybdenum steel? Perhaps I missed the point.

MR. TEMPLIN.—I do not think it is advisable to go to the extent of giving a long list of the parts made of aluminum. It varies somewhat with the engine. I think there are representatives here from aircraft engine makers and it might be much better if they would contribute a little information to answer the question. Cylinder heads are one outstanding part; the pistons and crankcases, especially the drop-forged crankcases, certain nose pieces, timing gears, intake manifold, etc. The list is rather extensive.

MR. STOUGHTON.—How about the proportion; is that about right?

MR. TEMPLIN.—I would not want to commit myself on that. The engine makers might give you some figures.

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[1] Chief Engineer of Tests, Aluminum Co. of America, New Kensington, Pa.

[2] Professor in Charge, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

MR. JEROME STRAUSS.[1]—Replying to Mr. Stoughton, my comment was somewhat more limited than he understood it to be. Of the *corrosion-resisting steels,* the two types of chromium-nickel steel mentioned are likely to be of more general use.

MR. H. J. FISCHBECK.[2]—In reference to Mr. Stoughton's question, the Pratt & Whitney wasp motor contains approximately, by weight, 45 per cent aluminum alloys, 48 per cent steel and iron, 6 per cent magnesium, copper, brass and bronze, and the remainder rubber, paper, asbestos, etc. Some of the parts made of aluminum alloys are the crankcase, blower section, rear end section, nose section, pistons and cylinder heads.

MR. H. S. RAWDON.[3]—I should like to ask Mr. Templin whether he is in a position to tell us what the prospect is of getting aluminum-coated duralumin tubing? The sheet material has proved so very satisfactory that everybody is hoping that tubing will soon be available.

MR. E. H. DIX, JR.[4]—Alclad tubing has been made experimentally; we hope that in the very near future it may be commercial. As is probably known, aluminum tubing is made by two processes, one known as "cupping," in which a flat disk is the start of the process, and the other by extrusion. Now it is perfectly possible to make a flat Alclad disk and then form it into tubing; however, duralumin tubing is difficult to make by the cupping process and some troubles have been encountered. Most of these have been overcome, and I think it is only a question of a few months when tubing will be obtainable.

MR. LEOPOLD PESSEL.[5]—In addition I would say that it is possible to spray aluminum both on the inside and outside of tubing. It is possible to apply an aluminum coating to other metals by means of the metal spraying process and a special attachment of the commercial metal spraying machine permits the application of a sprayed molten aluminum coating on the inside of tubing. This affords a very effective protection to duralumin.

MR. P. V. FARAGHER.[6]—I should like to speak of a type of material which has received some considerable use, particularly in lighter-than-air aircraft construction, namely, a duralumin type of material, which, after heat treating and aging, is given a slight amount of cold working. The cold working is so regulated as to produce a material increase in the yield point, a somewhat smaller increase in tensile strength at some sacrifice in ductility or elongation. By carefully controlling the amount of cold working after heat treating and aging, very good ductility may still be retained, although less than that of ordinary 17ST or duralumin. The radius of bends must, in general, be increased by an amount equal to about one thickness of the sheet as compared with that which is sufficient for the sheet before strain hardening.

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[2] Pratt & Whitney Aircraft Co., Hartford, Conn.

[3] Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.

[4] Metallurgist, Aluminum Research Laboratories, Aluminum Co. of America, New Kensington, Pa.

[5] Metals Coating Co. of America, Philadelphia, Pa.

[6] Metallurgist, Aluminum Co. of America, Pittsburgh, Pa.

This sheet was developed to meet the requirements of the design of the rigid dirigible airship which is being built by the Goodyear Zeppelin Corporation for the United States Navy. The specifications called for a minimum yield point of 42,000 lb. per sq. in. and a minimum elongation varying from 10 per cent in 2 in. for the thinner gages to 12 per cent for the thicker material. The sheet which was supplied had an average tensile strength of about 62,000 lb. per sq. in., an average yield point of 47,000 lb. per sq. in., with the elongation safely above the minimum requirements.

Extensive tests have shown that this material shows no loss in corrosion resistance as compared with ordinary 17ST or duralumin.

Mr. Templin has not been able to include this material in his paper since it has been decided only in the past week to offer this material to the general trade. The Aluminum Company is increasing its rolling capacity and these developments have progressed to the point where it is possible to solicit orders for this type of sheet.

This product, designated 17SRT, is not available in quite the same range of sizes and thicknesses as the ordinary 17ST, but equipment is being installed to extend the present manufacturing limits as rapidly as possible.

This product with its higher yield point offers still further possibilities from the standpoint of weight saving in the design of aircraft as compared with the materials which have previously been used.

MR. W. C. CLAYTON.[1]—Mr. Johnson draws attention to the question of the minimum permissible wall gage of steel tubing to be welded into aircraft structures. This is a most important question as it has an important bearing on the strength-weight ratio of the structure.

The fuselage of an airplane is designed by ten different loading conditions resulting in stress reversals so that nearly all member sizes are determined by column loads. Many of the members come within the long column (Euler) range where the strength of the member is not affected (theoretically) by ultimate fiber stress of the material, but only by the modulus of elasticity, length, and moment of inertia. Of these, the moment of inertia is the only one that can normally be varied at will by the designer. The only way to reduce the weight of a given structure of given material without reducing the strength is to increase the diameter of the columns and reduce the wall gage. This increases the moment of inertia which reduces the slenderness ratio of the column, often bringing it within the short column range where the high fiber stress of alloy steel becomes a distinct advantage. There are two factors limiting the extent to which the diameter can be increased with reduction in wall gage. The ratio of diameter to wall thickness may become so great that the member may fail by local buckling; this likelihood could be guarded against by using a limit of say fifty to one. (The English use a much higher value than this.) The other possible source of trouble is the likelihood of getting the wall too thin for welding. Since the adoption of welded steel tube structures in this country about eight years ago, 0.035 in. has been used as a minimum wall gage. In the meantime considerable progress has been made in the development of welding torches for thin gage welding, and in the technique of welding. In view of the fact that the welds rarely every give trouble where reasonable precautions have been used, it would seem reasonable and desirable to drop down to 0.028-in. wall on tubes of 1 in. or smaller on all-welded structure.

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[1] Assistant Chief Engineer, Pitcairn Aircraft, Inc., Willow Grove, Pa.

MR. H. A. BACKUS.[1]—In respect to Mr. Clayton's comments, I think perhaps Mr. Johnson had in mind a rather broad generalization for the whole aircraft industry. I imagine that he wishes to be conservative and to persuade manufacturers not to use tubing of such minimum wall thickness that they might accidentally get into trouble, particularly where they attempted welding. It is a matter of expediency that dictated these particular sizes.

MR. CLAYTON.—I was going over some blueprints a short time ago of an English designed plane. The English have been doing a great deal of drawn and rolled steel strip construction of very thin gage. It is only in the last year that they have permitted welding at all. The entire structure of this English plane was of welded steel tubing having a wall gage of 0.028 in. An American manufacturer could not possibly compete on a strength-weight basis with this machine. The English must be getting fairly good results or they would not continue to use this thin gage tubing. If good results can be gotten with thinner gages, we ought to look into it and recommend that the Department of Commerce change the requirements. I took what Mr. Johnson said referring to thinner gages, as the handwriting on the wall pointing to the use of thinner gages. Possibly we just carry on because we have been using the heavier gages without question for the last eight or ten years.

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MR. STRAUSS.—While not wishing to discourage such thin sections, I think we ought to bear in mind the possibility of both external and internal defects becoming rapidly much more serious as the thickness of the material is decreased.

MR. J. J. CROWE.[1]—I agree with the statement that it would be an improvement in welding technique and that it is possible and practicable to weld tubing of 0.028 in. wall thickness. Of course it requires more care and skill than is required for the heavier gages.

MR. L. B. TUCKERMAN.[2]—In an investigation that is being carried out at the Bureau of Standards, we have been testing the characteristics of various tubing. In connection with this investigation we desired to repeat some of the work done in England on very thin-walled tubing. Ratios of diameter to thickness as high as 100 have been used there in actual aircraft construction. These were not seamless but formed and riveted tubes. Experiments with ratios as high as 250 have been carried out.

So far we have been unable in this country to secure tubing with diameter-thickness ratios greater than 50.

With increased demand for strong and light construction in aircraft it would seem that the production of lighter walled tubing than is at present available in this country would be desirable.

In our tests no case of crinkling failure was found up to a diameter-thickness ratio of 50 so that from a structural standpoint higher ratios offer promise.

One of the main objections to very thin-walled tubing seems to be the ever present fear of local accidental damage by some careless action such as a misstep or a dropped tool. However, the successful use of high ratios abroad indicates that this danger can be adequately avoided.

MR. LEON CAMMEN.[3]—I should like to add a little to these papers, as to the practices, some of them actually in use abroad and some of them as yet experimental, which have not been mentioned here. In the first place there is a very interesting development in England by the Hurst people, the production of cast-iron sleeves for airplane engines. These sleeves are very thin and have extremely good wearing qualities. They have succeeded in producing centrifugally, sleeves with bosses on them.

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[2] Assistant Chief, Division of Mechanics and Sound, U. S. Bureau of Standards, Washington, D. C.

[3] Assistant Editor, American Society of Mechanical Engineers, New York City.

Next, in the field of light metals, there has been some very interesting work done in Germany and France, but particularly in Germany, in the production of alloys containing lithium and cerium. The effect of cerium in such alloys as silicon and aluminum is well known here, but they succeeded there in considerably improving alloys of the duralumin type by the introduction of cerium, which cannot be discovered in the alloy. Lately they have been doing work on adding lithium to aluminum alloys, and I understand that this has been very successful.

Next, in the field of heavy alloys, here again there has been a very interesting development in Germany, chiefly with the Shocker people, who have added beryllium to chromium-nickel and nickel alloy steels with remarkable improvement in the results. I know that considerable work on beryllium has been done in this country but chiefly in the field of light alloys where its addition does not seem to produce any startling improvement. In Germany, however, they are adding it to heavy alloys, such as iron-base alloys, and are obtaining very interesting results.

Finally, there is one material which has not been mentioned here at all and which I believe deserves very serious attention from aircraft designers, and that is modified monel metal. You are all familiar with monel metal as such, of course, and know that on an average it has about the same strength as low-carbon steel. It does not have, however, any hardness to speak of and is comparatively low in elastic limit. Of late, however, certain modifications of monel metal have been developed by addition of aluminum in this country, and a very interesting alloy has been produced in Germany and in France by the addition of boron. The percentage, I believe, is around one and a half per cent. This boron-containing monel metal has been found to have a tensile strength of 130,000 lb. per sq. in. and an elastic limit in excess of 70,000 lb. per sq. in., which, in view of its non-corrosive qualities, would make it a very interesting material for certain parts.

There is one more development I should like to mention—an English development—and that is the production of swaged chromium-nickel parts. I had one piece which I tested and which showed a tensile strength of 185,000 lb. per sq. in. It contained 3.45 per cent nickel, 1.45 per cent chromium and comparatively low carbon. This swaging of parts, I believe, will play a very important part in airplane work, particularly in very small pieces.

MR. STRAUSS.—I should like to ask Mr. Cammen whether he knows if the boron-containing monel metal has any better hot working properties than the aluminum-containing monel metal?

MR. CAMMEN.—I do not know exactly to what extent, but the hot working properties of aluminum-containing monel metal vary with the content of aluminum; you can have the composition of aluminum vary from 3 to 17 per cent. In the lower ranges you get the very best working metal, either hot or cold; as you increase the percentages of aluminum, you get a very much harder metal, but a metal which gradually loses its workability and loses the hot-working ability faster than the cold-working ability. I understand that boron-containing monel metal is remarkably plastic when hot, but is not a good cold-working metal. I might mention that the Bureau of Mines, in some of its work on boron-containing iron alloys, has found that there is a certain temperature above red heat at which the boron-containing iron can be kneaded practically like dough, but it is rather brittle when cold. I believe the same behavior is retained in the case of monel metal.

MR. STRAUSS.—May I ask Mr. Cammen how the ductility of the modified monel metal compares with steel, and the corresponding properties?

MR. CAMMEN.—My own work was limited to monel metal containing between 3 and 5 per cent of aluminum, and I found that it is approximately the same as that of, say, 0.35-per-cent carbon steel. That means that it has ductility up to a given point and then drops; it does not draw out to the sharp point of very low-carbon steels.

MR. H. A. ANDERSON.[1]—I was struck by the encouraging information in Mr. Johnson's paper that certain steel manufacturers are now supplying carbon steel sheets and strips which can be heat-treated so as to give equal ductility in all directions, thus permitting the formation of fittings without regard to the direction of rolling. Mr. Johnson points out that such uniform directional properties may be obtained in carbon-steel strip which is made from hot-rolled strip, severely worked by cold rolling, annealed to obtain an equi-axed grain and finally given a light draft for surface finish. I should be interested in having Mr. Backus, or Mr. Knerr, give us some information about the time and temperature of anneal required to produce this equi-axed structure.

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[1] Metallurgical Development Engineer, Western Electric Co., Chicago, Ill.

Referring to Mr. Templin's paper, the aircraft industry, young as it is, has already made substantial contributions in the development of new materials which have been adopted for use in the communication industry. The quality standards in both of these fields are exceptionally high. We have made use of the light alloys, which have been developed largely as the result of aircraft demands, for diaphragms and other parts of telephone apparatus. In connection with the statement by Mr. Templin on the beneficial effect of the Alclad coating in cutting down the vibration of the aircraft members, I should like to point out that that feature is, of course, a deterrent to the use of Alclad material for transmitter diaphragms. However, the latter apparatus, using duralumin sheet less than 0.002 in. thick, requires maximum corrosion protection and it is hoped that some satisfactory solution to permit the use of Alclad sheet for diaphragms will be found.

THE CHAIRMAN (*Mr. H. C. Knerr*).[1]—Mr. Anderson's first question, I understand, refers to the production of thin sheet steel having uniform ductility and bending qualities in both directions of the grain. Does Mr. Backus care to discuss that?

MR. BACKUS.—I am afraid that I am not qualified to say anything about that from the standpoint of the manufacturer. As for the ordinary working of the material in the shop and in the testing machine, it is substantially the same in both directions.

MR. A. L. DAVIS.[2]—I believe it has been shown that if normalizing temperatures (1650° F.) are used on steel sheets, in continuous furnaces, an equi-axing of grains is secured which would not be secured in the customary old fashioned low-temperature anneals. Physical properties are enhanced accordingly.

MR. KNERR.—The aircraft manufacturers are indebted to the steel manufacturers for producing a splendid material, in spite of their original objections to the Government specifications. These included, among other things, a fairly severe bend test calling for bending either way of the grain, through 180 deg. over a diameter equal to the thickness, in sheet steels capable of being heat treated to high tensile strength. The steel manufacturers at first insisted that this was another one of the "impractical" Government specifications which could not be met, but they went ahead and are now producing a material which far exceeds that quite severe bend test. I have seen a great deal of material which, in the annealed state, can be bent flat upon itself along the grain without showing any sign of fracture.

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[1] Consulting Metallurgical Engineer; and President, Metallurgical Laboratories, Inc., Philadelphia, Pa.

[2] Research Metallurgist and Engineer, Scovill Manufacturing Co., Waterbury, Conn.

MR. BACKUS.—The effect of low yield point and of low elastic limit of these 18 per cent chromium, 8 per cent nickel alloys is a handicap in contrast with the use of low-carbon stainless iron. I wonder if there is any possibility in the future of these particular physical properties of the 18 per cent chromium, 8 per cent nickel alloy being improved so that we can have an alloy which will be more generally useful.

MR. STRAUSS.—Austenitic alloys generally are characterized by low elastic properties. It is mentioned in the paper that cold working followed by low-temperature heat treatment greatly increases the elastic strength of these steels, and I do not doubt that alloying with other elements which will not be detrimental to the desirable properties of the alloy, may somewhat benefit elastic strength, but I do not think we can ever expect in an austenitic steel to obtain the high elastic ratios that are likely to be secured from materials which harden by thermal treatment.

MR. STOUGHTON.—I think we all know that the Europeans use silicon-manganese steel for springs on cars and we use chromium-vanadium steel, preferably. I wonder what they use on airplanes as regards springs? I have often wondered whether the Europeans use silicon-manganese springs on cars because they are not subject to habitual detours such as we have here. I should like to know what the practice on airplane springs is.

MR. STRAUSS.—I do not know that I can reply to that directly, because I am not familiar with their practice in aircraft springs, but I think that one may account for the use of the silicon-manganese steels abroad largely because there has been no particular effort to bring to the attention of European manufacturers in the last few years the advantages of chromium-vanadium steels. That is being done at the present time, but has been really very much neglected in the past. However, it is rather important to note that one very prominent American manufacturer of automobiles has recently changed from silicon-manganese springs to chromium-vanadium springs because of the difficulties he was experiencing with his exported products.

MR. H. G. RUNDE.[1]—A major portion of the helical springs so far used on aircraft have been plain carbon steel. In the flat spring there has been some chromium-vanadium steel used and a very small amount of chromium-vanadium steel in the helical springs. The major portion, however, has been of plain carbon steel.

MR. B. C. BOULTON.[2]—I am not very familiar with springs as such, but we have been making some investigations ourselves and find that it is a fact that the weight varies inversely, I think, as the square of the allowable fiber stress. We were requesting several spring companies to give us better grade springs. We have been getting material of about 140,000 lb. per sq. in. torsional strength, and I think recently of a torsional strength as high as 160,000 lb. per sq. in. Chromium-molybdenum steel is employed very largely for springs, and I think that some chromium-vanadium steel is used.

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[1] Chief of Materials Department, Curtiss Aeroplane and Motor Co., Garden City, L. I., N. Y.

[2] Keystone Aircraft Corp., Bristol, Pa.

MR. STRAUSS.—There has been considerable use of chromium-vanadium steels for landing gear springs, but now that the last speaker brings up the question of high unit stresses, it may be of interest to note a steel originally developed for another purpose which has been applied to round wire springs. It has a very complex composition, but happens to work and work very well, and that is a steel containing about 0.50 per cent carbon, 2 per cent silicon, 1 per cent manganese, 1.3 per cent molybdenum and 0.3 per cent vanadium. It has very high elastic strength combined with very high ductility.

MR. F. T. SOMERS.[1]—We have been using silicon-manganese springs for the past two years, due to the trouble experienced with chromium-vanadium steel, and have had no trouble since in our landing gears.

MR. KNERR.—Chromium-molybdenum steel tubing of the same composition as used in fuselages has been made into springs, and heat treated, showing a saving in weight of about one-third as compared with a solid carbon steel helical spring of equal strength.

MR. T. N. HOLDEN.[2]—I think the plain carbon steel has been used mostly in valves for aircraft engines, although some people like the chromium-vanadium spring, but it has been a source of trouble.

MR. R. R. MOORE.[3]—To my way of thinking, the spring problem resolves itself into two main divisions: namely, whether the spring is to be subject to rapidly repeated stresses or whether the spring is subject to occasional stresses. The valve spring problem becomes complicated due to installation conditions. For instance, a heat-treated chromium-vanadium steel valve spring works out very well where the temperatures of exhaust gases are high enough to draw the temper of music wire—because this chromium-vanadium steel valve spring is hardened and then drawn at a temperature higher than the temperature reached in the spring due to hot exhaust gases. The music wire spring, which is not heat treated, will be considerably softened by the hot gases and, therefore, lose its tension. On the other hand, I believe that the music wire spring is more free from defects and, therefore, more desirable for continuously repeated stresses. Springs for landing gears, if adequately designed, do not have to have the same quality as is required in valve springs because they employ much greater sections of material and are not subjected to as many repetitions of stress.

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[1] Fairchild Aircraft Co., Farmingdale, L. I., N. Y.

[2] Metallurgist, E. W. Bliss Co., Brooklyn, N. Y.

[3] Chief Metallurgist, Wright Aeronautical Corp., Paterson, N. J.

WOOD IN AIRCRAFT CONSTRUCTION

MR. CROWE.—I believe Mr. Trayer, in his paper, stated that design values are based on average values. It seems to me that we are likely to get in trouble if we base design values on averages rather than on minimum values.

MR. L. J. MARKWARDT.[1]—The design stresses for aircraft wood presented in Table I of Mr. Trayer's paper are, in most cases, not actual average values. They were, however, derived from average values after taking into consideration the variability of the material. Studies have shown, for instance, that variability curves for wood are commonly asymmetric or skewed, with more values falling below the average than above. Consequently, in arriving at the design stresses reduction factors were applied to allow for skewness and variability, and in a similar way other factors were provided for.

The design values presented were prepared by the Forest Products Laboratory in cooperation with the Bureau of Aeronautics, Navy Department, and the U. S. Army Air Service, the objective being to obtain values equally dependable with those for other material. They have been in use for many years and I think experience has demonstrated their dependability.

MR. BOULTON.—I might suggest a further answer to that question; I believe that the inspection, especially for wood for use in aircraft, is much more rigid than for building or general use. For many structures the strength can actually and economically be found without destroying the specimen, as, for instance, in a strut where the ultimate strength can be easily determined, and even in a beam the modulus of elasticity can be readily determined. I know that the procedure for doing this was worked out in the latter part of the war production of planes so that it became a regular system of inspection in certain plants. That of course eliminates, to quite an extent, the low-grade material, so that one gets probably as good or better than the average in wood as actually used.

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[1] Assistant in Charge, Section of Timber Mechanics, U. S. Forest Products Laboratory, Madison, Wis.

MR. MARKWARDT.—In this connection, it should be emphasized that the application of the design stresses presupposes the use of material with a minimum specific gravity requirement and with defects practically prohibited. The specific gravity requirement eliminates material of inherently low strength, and I understand it is the practice in aircraft plants frequently to check up on that limitation in the inspection of material.

MR. STOUGHTON.—I notice the author says that a lack of uniformity in the quality of wood is perhaps the most important factor militating against its future use in large scale production. A paper by Mr. St. John in this symposium[1] regarding testing by means of X-rays mentions testing wood by X-rays. That would be a very important point, because the knots and rotten spots and other things in wood may be concealed. I think it would be very valuable if we could hear to what extent X-ray examination of wood has been used and with what results.

MR. MARKWARDT.—The question of inspection, not only of wood but of any material by means of X-rays, is a very interesting field, and I think it is coming more and more to the front. The idea of such inspection, however, is not new, because the British used it to some extent during the war. My personal reaction is that, as far as wood is concerned, X-rays are going to be of principal value in checking up on workmanship and manufacturing practice, particularly in regard to joints and fastenings. In this connection, I recall seeing X-ray photographs taken by the British to observe the size of screws employed and to check up on the fastenings. I believe X-rays will be of less importance in inspecting for knots and similar defects, because in the small sizes used for aircraft, defects usually give some surface or visible evidence of their presence.

MR. H. R. ISENBURGER.[2]—I should like to add a word on the X-ray inspection of wood. To my knowledge, there has been no X-ray work done on wood in this country so far. In England there was considerable X-ray work done during the World War to control, especially, faulty workmanship, but also to detect knotty wood and also in ply-wood, which is very important.

MR. L. HARRISON.[3]—In connection with the values we have for members, the load factors for airplanes are chosen on the basis of experience and the load factor changes with time as pilots change practice. As for the values which were used for wood, the strength values were applied with some rather satisfactory results when wood is used for the main structural material. These values refer to certain inspection practice. The inspector's way of going about things is handed down with methods of flying and types of planes, to conform more or less with that practice, and while we have had a certain number of crashes, very few of those crashes could be assigned to any defect in the strength of the wood. Generally speaking they were due to an inadequate knowledge of the loads which were placed on the aircraft.

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[1] See p. 147.

[2] Secretary, St. John X-ray Service Corp., New York City.

[3] Bureau of Aeronautics, Navy Dept., Washington, D. C.

The only importance, it seems to me, of using true minimum values, is in changing from a wooden airplane to a metal airplane, and in that respect wood has one considerable advantage, that is, that under normal conditions of operation, it does not deteriorate as metal does. We have found that wood, as a structural material for a number of years in the naval service, was much more reliable than metal during the same period, with regard to the main structural elements.

MR. PESSEL.—I should like to ask a question with regard to the fireproofing of non-metallic construction materials, like wood or textiles.

MR. MARKWARDT.—The National Lumber Manufacturers' Association cooperated with the Forest Products Laboratory in fireproofing studies, the results of which were published in the 1930 *Proceedings* of the American Wood Preservers' Association. Both organizations are now carrying on experiments on the fireproofing of wood. I do not know the exact status of these studies, but more will be heard of them in the future.

MR. CAMMEN.—There is no way of fireproofing wood at all, and no matter how you treat it, if it is in the flames long enough, it will burn. For airplane purposes, what is important is not absolute fireproofing but slow burning, so that in case of a crash it will not go up like tinder but will burn slowly. In this direction, two methods are being used, both of them more or less successfully. One is vacuum impregnation, which is substantially the same as impregnation against corrosion, but with somewhat different materials. About two years ago a very interesting process was developed in Germany which consists in first immersing the wood in a peculiar electro-conducting liquid for a certain period, say twelve hours. Then the wood is placed in another liquid, so that only the two ends of the piece are immersed; then the current is passed through the baths at the ends of the wood, with the result that during a certain period of time the current flows through and carries the impregnating material. I understand that this method has been used quite successfully and produces a wood that is very resistive to combustion.

Finally there is a third method which is very interesting, and that is impregnating the surface of the wood with fire-retardant materials, something along the line of case hardening. This, again, is done electrically, and later on an oil is forced into the wood under pressure.

MR. MARKWARDT.—The only additional thought I should like to leave is that some of these terms like "fireproofing" and "moisture-proofing" are used rather loosely at times. In most cases, the terms "fire-resistant" or "fire-retardant," or "slow burning" more properly express what is popularly referred to as fireproofing, just as moisture-resistant coatings are erroneously referred to as moisture-proof.

CORROSION PREVENTION AND PROTECTIVE COATINGS

MR. DIX.—There are a few remarks I should like to make in reference to the papers by H. S. Rawdon and H. A. Gardner. First, in connection with Mr. Rawdon's paper concerning the painting of Alclad sheets, we agree with Mr. Rawdon that, in so far as structural stability is concerned, it is not necessary to paint Alclad sheets except for such service as pontoons in sea water. However, there is a tendency for aircraft manufacturers to desire to paint for decorative purposes, and there is also a tendency to feel that since the paint is not required for corrosion protection, it may be slapped on to the Alclad sheet with perfectly satisfactory results. But this is certainly not true; it requires just as careful preparation of the surface for Alclad sheets as for ordinary duralumin sheets; in fact, I think even more careful preparation.

I know, for instance, in one test made on pontoons where duralumin pontoons were compared directly with Alclad pontoons, both pontoons being under identical service, the paint came off the Alclad pontoons and the conclusion was drawn that the Alclad sheet was not standing up as well as the duralumin sheet. However, after several years of service, the Alclad pontoons have been shown to be much tighter and freer from leaks than the duralumin pontoons. Now I think the explanation is this: when ordinary duralumin is heat treated there is a rather heavy oxide film formed on the surface and this gives a better base for paint than the very thin film formed when an Alclad sheet is heat treated. For instance, the anodic film is, as far as we know now, the best preparation for paint and the heat treatment of ordinary duralumin gives a film much thinner but somewhat approximating that obtained by the anodic treatment.

Now there is a tendency for some aircraft manufacturers to feel that the ten per cent of pure aluminum coating on Alclad sheet results in too great a loss in weight. I should like to point out that the ordinary aluminum pigmented paint weighs, I believe, about one-hundredth of a pound per square foot, so that two coats of this paint on both sides of a No. 20-gage sheet (0.032 lb.) amounts to just ten per cent, and this is the percentage of the Alclad coating. Of course, on thinner sheets than 0.032 in. the paint film is proportionally heavier. On thicker sheets the Alclad coating is heavier because it is still ten per cent of the total thickness.

Again, in Mr. Rawdon's paper, there is a mention that a manufacturer of pontoons has applied the anodic treatment principally for the protection of rivets. I should like to bring out the importance of the electrolytic protection of rivets afforded by the pure aluminum coating of Alclad sheet. We have just completed a year's exposure of riveted samples in the salt spray. Riveted joints employing normal duralumin rivets in both cases were used; with the Alclad sheets the joints were roughly twice as strong after a period of one year as the same rivets in the duralumin sheets.

Also in connection with Mr. Rawdon's paper, I did not observe any reference to a warning against using dissimilar metals in contact. Of course aluminum suffers whenever there is another metal present, with a few exceptions; zinc, for instance, is an exception and I believe that zinc actually protects aluminum under some conditions. Copper, brass and monel metal are very bad for aluminum. All this is generally known to aircraft manufacturers, but there is one point that is perhaps not so well recognized, and that is that stainless steels which would be used because of their corrosion-resisting qualities, might be thought to be better in contact with aluminum than ordinary steel. Unfortunately that is not so, because the difference in potential between aluminum and stainless steels is nearly twice that between aluminum and ordinary carbon steels, the aluminum suffering in each case.

In connection with Mr. Gardner's paper, I notice a statement in several places in the paper concerning certain of these vehicles, that they will withstand a baking at a temperature of 250° F. for a period of one hour with satisfactory results. Although that apparently is not specifically recommended, yet I think we should bear in mind that such elevated temperatures are dangerous in connection with duralumin type alloys because they produce a marked lowering in corrosion resistance. Now just where that line may be drawn I am not sure, I have a feeling that this treatment of 250° F. for one hour is just on the border line; in other words, Mr. Gardner may have had this under consideration and may have found that temperature satisfactory, but I certainly would not favor any higher temperature or any longer time; and I merely mention that the high temperature treatment or accelerated aging, as we speak of it, is detrimental to the corrosion resistance of the duralumin type of alloy.

MR. BOULTON.—I should like to comment on two points that Mr. Dix mentioned. In the first place, in connection with the painting of Alclad, I believe both the Army and the Navy require exactly the same painting on Alclad, and in the case of the Navy, other treatment, that is given to straight aluminum alloys. We tried to get out of anodic treatment when we used Alclad but could not. I remember a discussion with Mr. Dix and also the Navy some time ago; they said they highly recommended anodic treatment; in other words, the Alclad is tossed in as additional protection. That brings up a neat little point Mr. Dix made about the saving in weight. To be sure his point is quite correct—the Alclad only weighs as much as the paint—but you have got to put the paint on too. Is not that correct?

MR. DIX.—Well, that is a matter of opinion; so far as I am concerned, if I am going to ride in a plane that has been under corrosive conditions, I prefer the Alclad coating to any amount of paint you can put on, because the paint is easily scratched off and the area where it is scratched off is open to attack. In the case of the Alclad material, you have protection even after abrasion. As to the requirements of the Army and Navy, I am not in position to comment, but if you have to put the same amount of paint on an Alclad sheet as on a duralumin sheet, you of course lose the added weight of the coating.

MR. BOULTON.—There is one other question I wanted to ask in connection with rivets. It is my understanding that if a rivet is put on an Alclad sheet without paint being previously put on the sheet, the electrolytic protection is extended to the rivet, but it is also my understanding, that if you painted the sheet before riveting, as is usually required (the sheet is easily painted immediately after cleaning and then assembled in construction), you thereby insulate the Alclad from the rivet and no longer have the electrolytic protection. I should like to ask Mr. Dix if he would not clear that point up, namely, if you insulate the rivet from the Alclad with one or two coats of paint, would the Alclad still protect the rivet?

MR. DIX.—I cannot speak from actual experience, but certainly as you ask the question, if the rivet is electrically insulated from the sheet, of course you cannot have any protection. If corrosion is started on the head of the rivet, it will undoubtedly cause the paint to peel from the surrounding sheet, and then I would anticipate the electrolytic action would cause sufficient protection to prevent any corrosion, but undoubtedly the paint would come off the rivet.

While we are talking about rivets, I may say that recently we have examined a number of rivets that have been cut from hulls—you are all familiar with the case where three or four rivets will show corrosion and the rest will be in pretty good condition. We have fortunately been in position to examine a number of these rivets microscopically, and nine times out of ten we have found that the rivets have been improperly heat treated and often entirely un-heat treated. They thus have a much lower corrosion resistance than the fully heat-treated rivets. In checking up on the heat treatment in aircraft plants, there seems to be a marked laxity in following what the manufacturers know to be good practice. Talk to a man in the office and he will tell you, "We heat treat our rivets at exactly the right temperature and quench them in cold water." Then walk out in the shop and you will see a boy eating his lunch, pick up a basket of rivets and drop them into a pail of water already steaming, and of course that absolutely destroys the corrosion resistance. I think the answer to most of our rivet corrosion problems is careful attention to the heat treatment carried out in the shop.

MR. BOULTON.—That raises a question recently brought out by the Bureau of Aeronautics. We had to send out some drawings for preliminary examination in which we used machine screws rather than rivets. They happened to be $\frac{1}{4}$ in. in diameter, and the Bureau asked why we used machine screws and stated that their preference was for rivets. Among other points we made in reply was that it is our understanding that machine screws, being already heat treated, tended to be more corrosion resistant than rivets. The Bureau replied by saying that, if the riveting were properly done, the rivets were just as corrosion resistant as machine screws. What is your opinion on that point?

MR. DIX.—I am inclined to agree with parts of both statements. It is possible also that the machining of the screws, removing any surface defects, may make the screws more corrosion resistant than the rivets. In addition I believe there is a possibility that the working of the head after heat treatment may to some extent lower the corrosion resistance of the rivet. However, that is largely theoretical and it is my belief at the moment that rivets, properly heat treated, bearing in mind cold-water quenching and a minimum period of time between withdrawal from the furnace and quenching at proper temperature, etc., should be entirely satisfactory and that anything that might be gained in regard to machine screws is not worth the added cost.

MR. BOULTON.—Mr. Dix made mention of dissimilar metals in contact with aluminum alloys. I might further suggest that probably a serious element in contact with aluminum alloys is wood, which tends to hold moisture in contact with the aluminum alloy. We have been building for a number of years hulls of composite construction and even at the present time are having considerable trouble with corrosion. We have tried to improve the protection, but wherever you have wood in contact with aluminum alloy, you have a very serious condition—I would suggest probably as serious as where steel and possibly bronze or brass are in contact, maybe not quite as serious as the latter. In the last specification which the Navy Department drew up for us, they specified a thin sheet of aluminum foil as an insulator. We have not ourselves tried that yet, but it is something that may be of considerable value. Our Navy inspector in the last week visited the Glenn Martin plant in Baltimore and came back highly enthusiastic with regard to a new type of coating or rather a modification of an old type of coating in connection with bitumastic. I was wondering if there is any one here from Glenn Martin that would describe that for us? It seems to be very remarkable.

MR. HARRISON.—Of course every one is familiar with the fact that our naval problem with respect to corrosion is possibly more difficult than that of any other organization except possibly the Pan-American Airways and a few organizations of that character. We feel, however, that the corrosion difficulties are in the way of being solved with regard to the light alloys. At present we are not so encouraged with respect to steel.

One of our difficulties which is of interest lies in the fact that our present methods of testing are not satisfactory with regard to any of the methods of protection. We are using the salt spray now and that gives us an answer that means something with regard to service life, but we specify long periods in salt spray before we say that a coating is satisfactory. That time must be speeded up.

The anodic coating was described. An anodic tank with new solution starts out nicely, but after a period of time the solution deteriorates. You can tell something about its effectiveness with regard to a particular plant by records of past performance related to current carrying capacity, etc., but we have no definite way of quickly testing an applied film; we can test by the salt spray, but this takes months. A quicker way should be devised.

The same applies to paint. The only reliable method of checking paint appears to be something of the same sort; two products from the same paint manufacturer, bearing the same label, but made at different periods are not alike. We test them by salt sprays, but the answer is not soon enough. The same thing applies to dope. In actual production work, contractors quite often alternate their orders for dope, because while the first order from one manufacturer may give a satisfactory supply, shipments may shortly become poorer. Often a proving of each shipment is resorted to; this takes much time. A quicker method of testing should be developed. In practice something has to be done to keep quality good.

Another point comes up in connection with Mr. Rawdon's paper, this matter of crevices in the joints. A coating is properly applied; you send it out in service; a satisfactory first life is secured. Now, Mr. Gardner has described the appearance of a complicated, involved duralumin structure that goes out and comes in for repair. The repair unit cannot take this structure apart, it cannot coat the fading surfaces again. The customary method of cleaning exposed parts for repainting has been to strip the coating by some method, rubbing, scraping or something of that sort, but that is not satisfactory; it is not a practical method. We at present are trying to use mild solvents, but the crevice difficulties enter into a matter of that sort and our effort now is to attempt to develop coatings which will last 100 per cent for a considerable period, say a year or two years, then to bring these coatings in and give them a light treatment such as a soap wash or something of that sort, and then to recoat the complete assembly as it is. The question of the length of service life and the ability to recoat the coatings is something that must enter into the choice of materials, type of structure and of protection.

The matter of bad rivets has been brought up by Mr. Dix. We found out that the reason for them is absolutely what he says, poor control of heat treatment in production. However, all the bad rivets do not show up at once. You cannot send a structure out for proof in service, leave in the good rivets and at one overhaul take out all the bad ones and be sure the others are good, because it takes a long time for paint coatings to deteriorate in some cases.

Our principal trouble now is with the steel alloys in service in airplanes exposed to salt water conditions. The duralumin corrosion problem appears well on the way to solution; for exposure to salt spray, the steel corrosion problem is yet unsolved. For that reason we are very much interested in stainless steel and are working actively on developing its usefulness.

MR. R. S. JOHNSTON.[1]—I should like to ask Mr. Gardner and Mr.

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[1] Director of Research, John A. Roebling's Sons Co., Trenton, N. J.

Rawdon for information in regard to the life of boiled oil coatings for the protection of interior cavities, also, whether there is anything that has a lower electrical conductivity than either the tung oil - rosin compound or the boiled oil? I am particularly interested in connection with what might be called crevice corrosion in signal systems under low voltage.

MR. H. A. GARDNER.[1]—Possibly Mr. Rawdon can answer that better than I can. Boiled oil is a good protective, but on the inside of a tube, a China wood oil (tung oil) compound is far superior to boiled linseed oil. I cannot give the life of the oil coating, but I should say that it ought to be good for two or three years, at least. Possibly Mr. Rawdon knows of some other compound that would answer the other requirements.

MR. F. B. OLCOTT.[2]—We find it necessary to use various types of corrosion-resisting steel in contact with aluminum alloys on ships. Mr. Dix, in his remarks, stated that the difference in the potential between stainless steel and aluminum is roughly twice that of carbon steel. I should like to ask Mr. Dix if this difference in the potential is the same between the austenitic type of steel represented by the 18 per cent chromium, 8 per cent nickel alloy, or the straight chromium stainless iron and stainless steels? In other words, is there a preferable type one should use if one has to place stainless steel in contact with aluminum alloy?

MR. DIX.—I am sorry that I do not have that specific information.

MR. BACKUS.—It seems that the emphasis so far has been principally upon the materials of finish with which we are dealing. However, I believe it is a matter of personal experience with most aircraft manufacturers that the efficiency of the method used in applying the coating has quite as much to do with the life of the finished product as the materials themselves. I wish to emphasize that very strongly. Unfortunately the finishing of aircraft is not a single process, it requires several coatings and there are a number of detailed steps in the procedure. In steel we have first to clean the steel, apply the metallic coating, either zinc or cadmium, then put on the primer and one or more top coatings. The importance of having a chemically clean—and completely clean—structure is important. The matter also of hardness of the individual coats as they are applied affects the durability of the finish of the succeeding coats. The completeness of the covering, too, which has to do with the filling of all crevices, the touching up of bolts, nuts and other parts afterwards, which may not have had the complete covering of the individual unit, is also an important matter.

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[1] Chemical Engineer, Institute of Paint and Varnish Research, Washington, D. C.

[2] U. S. Navy, Bureau of Construction and Repair, Washington, D. C.

There are three other points I should like to touch on. The anodic process is rather a complicated and costly procedure. It is useful not only for the partial prevention of corrosion, but also as a very excellent base on which to apply further coatings. I believe if it were possible to have some purely chemical process, it would save a great many manufacturers the expense of installing the electrical apparatus, and since other finishes are applied over that, it might serve its purpose satisfactorily. There is a thought also in the possible use of steels which are not completely stainless but might be termed more rust resisting, even if they do develop a slight brownish discoloration, which might be prevented by the addition of paint.

There is one point in connection with dope and paint which is highly distressing to all manufacturers, a point which has already been made by Mr. Harrison: namely, the fact that the formula and mixes vary so much from time to time. The large manufacturers have rather an extensive series of time tests which they run on the products the different manufacturers submit. It is a long drawn out, expensive process, and they must trust to luck for the product they are getting and let the product pay the penalty. I think it is distinctly the purpose, at least I hope it is, for this Society to develop specifications for materials of this character. I certainly think the time ought to be approaching when we can develop some specifications which are basic, at least, and have the manufacturer follow them; if this were possible it would simplify the question by starting out with something definite. We could work from that and develop better types. I suggest that as a bit of work for this Society.

MR. BRUTUS BROOKS.[1]—I should like to ask if Mr. Rawdon has given any method of protecting magnesium alloys?

MR. RAWDON.—Yes, we have started and have in process extensive tests on magnesium and several magnesium alloys, both in Washington and at the Canal Zone. The results, however, are not yet ready to be given out.

MR. F. W. HOPKINS.[2]—I should like to ask Mr. Gardner a question; when coating fabrics with clear and pigmented dope as a finishing system, which is more important, flexibility or the tautness, if one has to be sacrificed for the other?

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[1] Materials Department, Chance Vought Corp., Hartford, Conn.

[2] Assistant Manager, Technical Department, Murphy Varnish Co., Newark, N. J.

MR. GARDNER.—I think tautness is the more important property.

MR. HOPKINS.—Do you think that is the consensus of opinion?

MR. GARDNER.—I do not know.

MR. HOPKINS.—Of course we have been asked for both, but so far we have been unable to obtain both.

In the manufacture of a primer for duralumin, do you feel that a spar varnish, which has considerable durability alone, is a better type of vehicle than a short oil varnish which might have greater adhesion? Of course the average system consists of primer, enamel or lacquer. Primer made with a spar varnish might give more durability than one made of a shorter oil vehicle, but with a shorter oil vehicle better adhesion to the metal might be obtained and also between finished material and the primer coat, since such a primer would undoubtedly have better drying qualities.

MR. GARDNER.—I think if you go to something that gives you quick drying as a primer, you are bound to get into difficulties on a long-time exposure. We found that linseed-oil paints are best, but are too slow in drying. The type of primer containing zinc chromate was quite satisfactory; the Navy Department used that quite extensively.

MR. HOPKINS.—Have you done any work on lacquer primers to any extent?

MR. GARDNER.—Those that I investigated failed very rapidly.

MR. HOPKINS.—That is, your entire system, not when the primers were tested alone?

MR. GARDNER.—Yes, the entire system.

MR. HOPKINS.—We feel that if you test a primer alone you do not get as satisfactory a result as you do when a finishing material is applied over the primer. We have found, especially in the salt spray test in conjunction with several exposures to heat, that a primer with a shorter oil vehicle than a spar varnish is just as durable and will protect the duralumin from corrosion as well as the spar varnish vehicle.

STAMPINGS, FORGINGS AND CASTINGS

MR. T. H. HUFF.[1]—We are very much interested in the paper by Mr. Runde because it is along just the line that we have been studying for several years. One question that has developed is the value of aluminum alloys in the form of castings under shock load and the advisability of making use of aluminum alloys in landing gear fittings, tail skid fittings and parts of that sort. I notice in Fig. 6 of the paper an interesting comparison between a cast-aluminum tail skid fork and a welded tail skid fork. I was wondering whether experience had indicated that the cast-aluminum fork was entirely satisfactory for a replacement to the steel fork? That is a point that is interesting to us because we have just been making a study of that particular point, and any information that you might have with regard to that particular field would be of very great interest.

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[1] Fokker Aircraft Corp., Passaic, N. J.

MR. RUNDE.—I have no information on this particular item here, which was obtained on information from other plants, but I know we have used castings in places such as this. In an oleo wheel which we developed some time ago and used to a certain extent, the shock absorbing mechanism was incorporated in the oleo wheel. A great many of the parts were aluminum-alloy castings and the service we have had on them so far has shown them to be entirely satisfactory. Where failures did occur they were in most cases attributed to design rather than the material itself.

MR. BOULTON.—We use castings very extensively in control systems. You have to be very careful in the design of castings to be sure that there are no sharp corners, etc.; in other words, the foundry can only go a certain distance in getting sound castings. If the design is improper, no amount of good foundry practice will improve it, but it has been our experience that castings have proved in general satisfactory if used with due regard to their properties. We are experimenting now with a casting in a landing gear, an aluminum-alloy casting, in which the various struts fit, and are about to make a drop test of the gear. I am sorry that is not completed; it would have a direct bearing on the point in question.

MR. HUFF.—I should like to ask one more question, that is in connection with the use of the X-ray photograph of the casting in order to insure the soundness of the casting where it is to be used in a control part. In other words, we could have the X-ray photographs taken at the place of manufacture of the castings, but how accurate is the information we obtain from such X-ray photographs? and are we absolutely assured that if we have a good X-ray picture, that our casting in our stick control or pedal control is absolutely a sound casting?

MR. KNERR.—The fact that X-ray examination is being used in this work is a rather strong indication of its desirability.

MR. L. C. CONRADI.[1]—I am rather interested in the application of manganese castings for tail skids. It would be my offhand impression that the ground would generally be so soft that you would not realize the benefit of any cold working that the manganese steel would give you, and I am wondering just where, in aircraft, that application is justified and whether the landing ground would be hard enough to really obtain cold working.

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[1] Metallurgist, Lycoming Manufacturing Co., Williamsport, Pa.

MR. RUNDE.—The manganese steel shoe has been used for quite a long time but it appears now that probably the best properties of the manganese steel are not being developed in this particular application. I understand that in manganese steel, the best properties are developed under heavy loads, and that condition of course is not obtained in the particular application as a tail skid shoe. There are other materials which are now being used and which it is hoped will prove to be better, one of which is a chilled cast iron which has been specified by the Army air service. I have not had very much experience with it yet. It seems to be satisfactory if it is properly chilled. There was some difficulty at first in its not being chilled. There is also another material we are investigating. It is a chromium-manganese-nickel alloy, which, on test, so far, has proved to stand up better than the manganese steel shoe. I think, however, that the manganese steel shoe has been quite satisfactory.

AIRCRAFT ENGINE PARTS AND ENGINE FAILURES

MR. T. T. NEILL.[1]—The statement is made in my paper that the information contained therein is based upon approximately forty engine type tests. That was correct at the time the paper was written. Since that time we have been able greatly to increase our engine testing facilities, with the result that we have run over thirty engine tests in the last six months alone. The more recent tests have served to confirm the statements which were embodied in the paper.

The parts that are subject to failure are all the parts of the engine. We have had practically every part fail. That was true six months ago and it is still true. The recent breakages have in some cases been quite spectacular, perhaps more so than some of our earlier failures. A short time ago an engine blew an entire block clear of the case.

In my paper you will note the words "a few" used in some cases. I should like to say that recently our experience has been such that in practically all cases the words "a number" may be substituted in the places where you find the words "a few." For example, I stated that we had tested a few in-line engines. We have now tested quite a number. I stated previously that most of the engines recently submitted were able to pass the test. However, we had a little "epidemic" of failures just after the paper was written, so that that statement did not look nearly so true. Then we got in a group of engines, quite a number of which ran through, so we had an "epidemic" of engines that passed. On the whole I believe at this time I should say that the statement that most engines were now passing was perhaps a little inaccurate; the record is not quite so good as that. The conclusion which I drew previously as the indirect cause of the failures, the specific causes being taken up more in detail, was the lack of sufficient development work on the part of the manufacturers. I repeat that conclusion; I repeat it with more emphasis; it is painfully evident to us in many cases. By development work I mean the running of the engine under its own power on a test stand. By its own power I mean all the power it has, everything the engine will turn out. The tendency to run engines under light load on the ground and then take them into the air is entirely too common a practice with some of the smaller engine manufacturers.

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[1] Assistant Engineer, U. S. Bureau of Standards, Washington, D. C.

When an engine is being run on a test stand and failure occurs, as I have every reason to believe they frequently do, the logical step is to go back to the laboratory. I say go back because the manufacturer should have started there. The next place to go is the drafting room, with new material or design, then the shop, and then the test stand again.

MR. TUCKERMAN.—In the paper by Mr. Neill there is brief mention made of a type of failure that I thought required more emphasis. On page 106, in discussing connecting rods and crankshafts, it is stated that:

> "Many manufacturers stamp the cylinder number on the shanks of the corresponding connecting rod. Such practice on parts subject to repeated stress is to be condemned, marking with an electrical pencil being much preferred.
>
> "A few crankshafts have broken and although such failures are not common, they are doubtless the most serious from the point of view of danger. Like many other failures they wreck the engine, but in addition they are liable to permit the propeller to fly off or to tear the engine from its mounting, with a possible wreckage of the plane. Landing with a 'dead' engine may be serious, but if in addition the wing or fuselage is damaged, conditions are far worse. Poor design and poor material, with the emphasis on the former, appear to have been the chief causes of the few crankshaft breakages which have occurred. Sharp changes of section in the crankshaft bore at a highly stressed part, keyways with sharp corners and with screw holes to hold the propeller keys are some of the features of poor design which have been noted."

It seems to me that all of us who are interested in the development of aircraft engines who have any influence whatsoever with manufacturers, should somehow or other emphasize that in pieces which are subject to high alternating stresses it is necessary to have a good surface finish, to avoid sharp angles, especially sharp re-entrant angles, and to provide sufficient fillets. I have been called in by the Bureau of Aeronautics, by the Department of Commerce and by others to examine all sorts of failed parts where the failure has been caused by neglect of these precautions. It would seem that by now manufacturers would know that it is not good practice to stamp the name of the firm across the middle of a highly stressed propeller blade; that it is not good practice in a crankshaft to machine out a little bit of a fillet and leave all the tool marks running around it; that it is not good practice to leave anywhere sharp re-entrant angles or rough surfaces in parts subject to high alternating stresses. I think that the paper could well emphasize that one particular point much more than has been done.

MR. I. S. REITER.[1]—Referring to Mr. Neill's paper, I had access to about twelve metallurgical reports made on the failed parts of what you may call experimental engines, engines being developed for the first or second time, and I found that the large majority of the failures were due to improper machining, with improper heat treatment and design taking only a small part.

MR. H. F. MOORE.[2]—The remarks of the last speaker together with the remarks of Mr. Tuckerman lead me to wish to add something from what you may think is a rather academic viewpoint. I believe that in connection with the machining of re-entrant angles (stress raisers, as Mr. Gillett has called them), the fact should be noted, that ordinary steels vary greatly in what may be called *tenderness* or sensitivity to stress raisers, and that the modern heat-treated alloy steels are, in general, much more "tender" to these stress raisers than are the low and medium-carbon steels. The extreme illustration of lack of "tenderness" was given by Mr. Kommers in his paper on cast iron.[3] You can put all the stress raisers you want into cast iron and they do not greatly hurt it; stress raisers in the form of graphite flakes are in cast iron already. If, however, you have some of this beautiful heat-treated alloy steel, one tool mark or punch mark, or one sharp screw thread may do a great deal of damage.

We have not as yet any real technical name for this quality and no well-known means of measuring it, but I believe this quality of tenderness and sensitiveness to damage by stress raisers is one which the maker of such parts as airplane engine parts will have to consider in the future, in fact will have to consider now. Of course in spite of its tenderness, heat-treated alloy steel is far superior in strength to cast iron or to ordinary structural steel, but with alloy steel care in avoiding sharp shoulders, nicks, and other stress raisers is of relatively greater importance than in structural steel.

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[1] Main Laboratory, Bethlehem Steel Co., Bethlehem, Pa.

[2] Professor of Engineering Materials, University of Illinois, Urbana, Ill.

[3] J. B. Kommers, "The Effect of Under-Stressing on Cast Iron and Open-Hearth Iron," see p. 368.

MR. FISCHBECK.—As manufacturers of aircraft engines we are in favor of the tests that are being made by the Department of Commerce to be assured that suitable engines are produced. Results of these tests have undoubtedly prevented a number of airplane failures which would have been injurious to the aircraft industry.

The hazard of deep stamping on parts should be brought more emphatically to the attention of the mechanic; also marks from rough machining, as a number of mechanics consider the cost too great to remove them.

Mr. R. R. Moore has given us a very excellent paper on the materials used in aircraft, but there is one thing I should like to mention—that aircraft engine manufacturers cannot use new materials until they are beyond the experimental stage, and have been used in the automotive industry for several years. This particularly refers to steel.

MR. CONRADI (*presented in written form*).—I have read Mr. Moore's paper on "Materials of Construction in Aircraft Engines" with a great deal of interest. Only brief mention is made of chromium-molybdenum S.A.E. No. 4150 steel as a substitute for S.A.E. steels Nos. 3140, 3250 and 3335 in the making of minor gears, studs, knuckle pins, etc. Inasmuch as chromium-molybdenum steel can be treated to give the same physical properties as the nickel-chromium steels mentioned above and in addition machines very much more easily I am wondering why it is not in general use for both minor and major aircraft parts.

The automotive industry, for instance, uses S.A.E. steel No. 4140 for axle shafts at the following Brinell ranges and corresponding minimum physical properties:

	BRINELL HARDNESS, 311 TO 340	BRINELL HARDNESS, 364 TO 418
Tensile strength, lb. per sq. in.	155 000	170 000
Elastic limit, lb. per sq. in.	130 000	150 000
Elongation, per cent	18	14
Reduction of area, per cent	50	48

It is likewise used for steering knuckles, steering arms, universal joint stub shafts and yokes. All parts are readily machined in a production way after heat treatment.

MR. BISHOP CLEMENTS.[1]—As a comparison of S.A.E. No. 4130 steel to a chromium-nickel steel, I much prefer heat treating the nickel steel because a much lower quenching temperature can be used. This lower quenching temperature requires less heat and less quenching oil, and also causes less decarburizing and less distortion. We use large quantities of chromium-molybdenum steel sheet, tube, bar and forgings for the reason it is about the best steel for welding. Most of this steel is heat treated after welding.

Referring to the remarks by Mr. Fischbeck, I think it is up to the aircraft builders to do what they can to develop new materials. I think they need new materials and have helped more in the development of the aluminum industry than any other manufacturer.

MR. REITER.—So far as chromium-molybdenum steel is concerned, I should like to mention the fact that some of the larger manufacturers of aircraft engines in the country today are using chromium-molybdenum steel for cylinder barrels. In doing this they can maintain the same Brinell hardness, approximately the same tensile strength and elastic limit as in the No. 1050 steel, but greatly increase the ductility and impact values. The reason for some manufacturers using chromium-molybdenum steel is that, with the same Brinell hardness as with No. 1050 steel, it is much more readily machined, and one manufacturer tells me that the additional cost of using the alloy steel over the No. 1050 steel is more than offset in the machining cost.

MR. W. H. HERSCHEL.[2]—On page 92 of Mr. Moore's paper giving the different kinds of bearing metals, I think it would be of interest if we could have some more information in regard to the relative amounts of bronze and white metal used in the bearings and how this compares with the practice in automobiles.

MR. R. R. MOORE.—In reference to Mr. Conradi's suggestion as to the chromium-molybdenum steels, there is no doubt that somewhat better elongation is obtained for the same tensile strength on the chromium-molybdenum steel than on the nickel-chromium steel. However, the advantage gained is not so great as to warrant immediate adoption of chromium-molybdenum steel. I quite agree with Mr. Clements' comment in regard to the fact that some trouble is experienced with chromium-molybdenum steels due to decarburization. However, I do not doubt that chromium-molybdenum steels will find an increasingly larger application. They are already used in airplane construction in tubing and sheet form. On large crankshafts a chromium-nickel-molybdenum steel is used due to the fact that it has a very good Izod value and hardens throughout very readily.

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[1] Metallurgist, Curtiss Aeroplane and Motor Corp., Buffalo, N. Y.

[2] Associate Physicist, U. S. Bureau of Standards, Washington, D. C.

In reference to Mr. Herschel's remark as to bronzes and white alloys, I think you will find that the aircraft engines, particularly the air-cooled type, use very little white alloy because the conditions are much more severe than in the automobile. An air-cooled engine runs considerably hotter than an automobile engine. After considerable experimental work with master rod bearings on radial air-cooled engines, the conclusion has been reached that white metal alloys are not desirable for such installation. The high-leaded bronze with the steel back will give more satisfactory service.

In reference to Mr. Fischbeck's remarks in regard to the development of alloys by the aircraft manufacturer, I believe that the aircraft manufacturer will either have to develop alloys suitable to his work or else encourage this work on the part of the metal producers. For instance, the development of aluminum and magnesium alloys has been given much encouragement by the aircraft industry; also the high-leaded bronzes, as previously mentioned, have a particular field in aircraft work.

In reference to Mr. Reiter's remarks as to the causes of failures, I would put design first, machining second, and heat treatment third. Of course design and finish are very similar in their effects, but I really think that most of the failures were design failures. There is no doubt that machining and finishing are very important in aircraft engine construction. This is due to the very light construction followed in order to keep the weight of the engine down. A very small scratch or notch becomes a very serious detriment to the life of the part.

Mr. H. F. Moore brought up a very interesting question. He mentioned the older metals, such as cast iron and low-carbon steels. This is a problem. Aircraft engines have to be made light and in order to do so heat-treated alloy steels must be used. Such engines cannot be built along the lines of the railroad locomotive. Mr. Moore also mentioned that there are so many stress raisers in a material like cast iron that a few more in the form of scratches or notches do not seem to make much difference. This means that the ratio of the endurance limit of cast iron to its tensile strength is not much affected by poor machining. While this is true, it must be remembered that the actual net endurance limit in the presence of these conditions is greater for heat-treated alloy steels than for cast iron. A similar comparison applies to open-hearth iron, which has a higher endurance ratio but not a higher net endurance limit than many of the heat-treated alloy steels.

MR. NEILL.—In reference to Mr. Reiter's remarks on failures due to poor machine work, I think his point is based on his own experience from the reports he has obtained. That seems rather natural; poor design is frequently obvious after the failures have occurred but not before. Hence these cases would not be brought to the attention of the steel companies as quickly as something that might be blamed on the material. Manufacturers often seem to like to blame the material companies, and it is then up to the latter to show that the heat treatment or machine work was poor. I think Mr. Reiter's conclusions are based on such reports which are not altogether representative.

SPECIFICATIONS, MATERIALS CONTROL AND TESTING

MR. R. W. WOODWARD.[1]—In the paper by Mr. Backus, there is one method of inspection of raw materials I should like to point out which I believe ought to have a much greater use in aircraft industries, and that is the spark testing of steel raw material. This method is simply holding the material against an emery wheel and comparing the nature of the sparks with a standard specimen. It is quite possible to determine carbon compositions within a very few points, and several of the alloy elements can also be qualitatively and in some cases quantitatively determined. In other branches of industry this inspection method is used for a 100-per-cent inspection of all raw material which is to receive subsequent heat treatment, and I see no reason why it could not be similarly used in the aircraft industry.

In Mr. Johnson's paper on testing there is one comment I have to make in regard to the hardness test, where he states, on page 125, that the Rockwell hardness, "E" scale, with a $\frac{1}{8}$-in. ball, gives more erratic readings than the Brinell tests. With the $\frac{1}{8}$-in. ball of course the impressions obtained are much more commensurate with the constituents of the casting and any variations which are observed are due to actual differences in hardness in the individual constituents of the casting.

MR. CAMMEN.—When we come to the specifications on testing, I notice that ordinary analysis is used, that is for carbon, sulfur, phosphorus, silicon and manganese. That means that we cover by our analysis about 99.5 per cent; the remaining 0.5 per cent we know nothing about; and yet we know perfectly well that the final result depends on that 0.5 per cent that is not shown by ordinary analysis. It makes a vast difference what quantities of nitrogen, hydrogen and oxygen are contained in this steel. It makes also a great difference whether or not some special material is present, as for example lead or alkaline metals. I believe that for aircraft we ought to specify 100-per cent analysis. There are already available methods of analyzing material commercially to 100 per cent, as by spectrum analysis, and I believe that the time has come when we ought to consider some such thing as spectrum analysis or other methods of analysis which would show up 100 per cent composition of material.

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[1] Consulting Metallurgist, The Stanley P. Rockwell Co., Hartford, Conn.

MR. R. R. MOORE.—I should like to add some comments in regard to the bend testing machine shown in Mr. Johnson's paper on page 122. It may be interesting to anybody who contemplates making bend tests, particularly on hard wire or sheets, to know that in developing this test we found that very minor variations in the bend radius had a remarkable effect on the test results. It is very important that the end of the radius blends to the flat face of the grip. Differences as small as 0.005 in., which would leave a hardly discernible mark on the surface of the radius block, were detrimental and affect results as much as one per cent. Ordinarily, as Mr. Johnson says, the bend test is regarded as a very rough and crude test. It is really a very sensitive test and is to be very carefully made.

MR. JOHNSTON.—An incident occurred the other day in testing that, to my mind, shows the need of standardization in one test at least. In connection with a bend test for music wire, in one organization the test was made by clamping the wire in a vise, putting a right angle bend in the free end and using that as a grip and lever to bend the wire down over the vise at the same time pressing with the thumb of the other hand to get contact of the wire at the vise. Another organization used a bending machine something like that described in the paper.

The bending machine gave about twice the number of 90-deg. right angle bends that were obtained by the other method. The operator who made the tests with the bending machine obtained the same number of bends using the other method, that is bending by hand. There is a difference there of almost two to one in that particular product, and that not only applies to one size of wire but to several sizes.

Some of our so-called simple tests apparently need further consideration, and if any one has trouble at times in getting material to do what is expected of it, it may be wise perhaps to look into the test methods.

MR. BACKUS.—In regard to spark testing referred to by Mr. Woodward, I quite agree that that can be of very considerable value. With satisfactory training it can be used as a desirable means of check testing.

With regard to 100-per-cent analysis, that might theoretically be necessary, but it is hardly justifiable practically unless we go to some such method as spectrum analysis. We cannot in practice either proof load or check ourselves 100 per cent at each and every operation as is theoretically necessary.

MR. BROOKS.—I should like to ask Mr. Johnson how to get the yield point of heat-treated aluminum alloys, in particular as he pointed out on page 121, "Horizontal scratches and deep gage marks may cause premature failure with low elongation, especially on aluminum alloys and heat-treated steel less than 0.065 in. in thickness."

MR. ANDERSON.—Answering for Mr. Johnson the comments made on his paper, I think that it is most essential, in making bend tests, to insure that the actual radius conforms to the nominal radius, if one wishes to obtain consistent results.

With respect to the relative merits of the Rockwell and Brinell hardness tests, the Rockwell "E" test referred to was developed by the Society's Committee B-6 on Die-Cast Metals Alloys and consists in applying a 100-kg. load on a $\frac{1}{8}$-in. diameter ball (reading the red scale). Statistical studies show the Rockwell readings obtained with this combination of load and penetrator are about as consistent for a given number of readings on die-cast test specimens as are a similar number of Brinell readings on the same material. In both cases the presence of blowholes and differences in the porosity of the material necessitates the making of a large number of observations in order to get an average value with a sufficiently low standard deviation.

In reference to Mr. Brooks' remarks about the method of evaluating the yield point, the common method, of course, is to determine the load or stress corresponding to an elongation of 0.5 per cent. More refined methods of determining the yield point of non-ferrous metals were discussed by Mr. Templin in his paper before the 1927 annual meeting of this Society.[1] I think that the best answer to the question is to refer the speaker to that paper.

The emphasis on the importance of horizontal scratches and deep gage marks on various forms of test specimens is perfectly valid.

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[1] R. L. Templin, "Methods for Determining the Tensile Properties of Thin Sheet Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part II, p. 235 (1927).

They may not affect the yield point, but they certainly affect the elongation, number of right angle bends to failure and the fatigue endurance limit.

MR. ISENBURGER (*presented in written form*).—Referring to the paper by Mr. St. John, the examination of aircraft materials by means of X-rays is based on the penetrating power of these rays. It refers to the testing of raw materials and to the examination of rough, semi-finished and finished products of high value such as castings, soldered or welded seams, etc., to discover faults within materials, such as slag, shrinkage, blowholes, cracks, porosity, and the like.

Of great importance are the X-ray examinations of metal castings which frequently have cavities or impurities. These X-ray pictures are a great help to foundrymen in general and to aircraft engineers in particular. It is our contention that the crack-ups not due to the failure of man-power are directly traceable to weak materials and undiscovered defects. In future, up-to-date manufacturers will find it desirable to apply X-ray inspection as a matter of routine. For the investigation of welded or riveted joints of fuselage members, too, this method is of great value. An X-ray picture will show whether there are cold shuts or other defects which are not visible on the surface.

The soundness of castings, like pistons, manifolds, crankcases, shock-absorber cylinders, cylinder heads and many other engine parts, is extremely important, and the X-ray is the only means by which the interior of the casting can be examined without destroying it or causing any physical or chemical change. In one instance a crankcase from a radial motor in service was successfully examined in an endeavor to locate an oil leak from the main part of the case into the manifold. All pistons of the trans-Atlantic airplane "Bremen" were X-ray inspected.

Forgings and welded sheets may be similarly inspected for internal defects. Serious waste in the metal working industry often occurs because of internal defects discovered in the work after considerable machining has been done. Claims for damages are sometimes made, because internal defects in parts which were not discovered when building the engine or plane have caused subsequent failure in service. Light metal ingots have been examined for their soundness before they were used in the production of fabricated parts, particularly airplane propellers. Both extruded and press-forged parts are being made from these X-rayed billets. A very important application of X-ray inspection is the determination of the depth of the counterbalance-hole in the hub section of aluminum propellers. Before using the X-ray, the lead counterbalance plug was drilled out, the hole measured and again filled with lead and then the propeller was balanced, a somewhat toilsome procedure. The X-ray inspection determines the depth of this hole accurately and cheaply.

Welded aluminum and steel sheets as well as welded fuselage members have been X-rayed very successfully. Flash, torch, butt, any kind of weld employed in airplane structures can be readily shown on the X-ray picture. For instance in one case a group comprising five pieces of chromium-molybdenum steel tubing and two reinforcing plates formed a single assembly. The details of all joints in this assembly show up nicely, including a region near one joint where the tubing was unduly thin just adjacent to the edge of the weld metal and unduly thick slightly further away. In another rejoin a crack was disclosed just outside the edge of the weld. This crack was not visible on the sand-blasted surface, but was discovered on the inside when the tubing was sectioned.

X-ray examination of welds can be very usefully applied to improve the welding process and to control and better the welders' work. Furthermore, it can be shown in an X-ray picture if interior defects not visible from the outside, like rolled out shrinkage holes, exist, which otherwise would appear only during tooling or machining, especially by cutting the material, and in many cases not before the plane crashed.

It may not be generally known that certain important joints of the British airship "R 101," after assembly have been X-ray inspected in place. This investigation involved using a high-power X-ray tube at a height of from 40 to 60 ft. above ground. The examination was successfully carried out, and the soundness of the joints put beyond all doubt. It is equally important to inspect riveted joints in aircraft structures, since very often the rivets bend and thus form a weak joint; this can be easily avoided by checking up by means of X-rays and replacing any such bad rivets.

MR. HUFF.—It still remains a question in some of our minds as to just how accurate the X-ray work is in connection with the more intricate castings of very large size that we may run into in some of the aircraft engines, crankcases and parts of that kind. The reason I bring this question up is that I have heard recently that there is some question about the advisability of using magnesium in crankcase castings due to the fact that possibly all of the defects that might occur in these castings would not necessarily be shown up in the X-rays that were taken of the crankcase casting proper.

Referring to the paper by Mr. Frost, I believe that, as we get into the more intricate designs of our aircraft parts, particularly with reference to metal structures, we are going to have to go into a study of our stresses by the photological method. Mr. Frost has had great opportunity to study this for a number of years at the Institute, and I know that he feels that it is something that will be of material benefit to the aircraft industry as time goes on. The work that he has been doing has not been practically acceptable to our welded steel structures or to our wooden structures, but I feel that in getting into metals we will be able to make use of the work he has done. I sincerely hope that more information will be forthcoming in order that we can apply it to every-day use.

MR. SOMERS.—With proper X-raying of castings one can get fine castings which are safe to use. However, last fall we had two different engineers designing two different ships. In the course of testing we suggested the control system, and in one control system all aluminum castings were used, all X-rayed, and in the other all bronze castings were used. In the test where we had aluminum casting, every casting failed, and in the case of the bronze castings, no bronze casting failed and the weights were not out of proportion. We got down to about the same weight with the bronze casting. The aluminum castings stood up to what they were figured and no more; in the case of the bronze we could have used higher figures.

MR. HARRISON.—In the course of my last few years at the Bureau I made at one time or other a trial of each of these methods of control and was satisfied that each was not in shape at the particular time to be used in actual, practical work. I was very hopeful that they would be further developed, and the literature here seems to indicate that they will be. There are certain specialized ways in which X-ray testing can be used, particularly on members which are of a symmetrical form. It can be used on ordnance parts, in particular, and will be of great advantage for 100-per cent inspection under quantity production conditions. During the War, it was used to some extent: for example, for certain fuses, which were passed in a continuous stream, and an operator continuously looked at the stream and rejected the poor ones very rapidly. I was familiar with the process as it was used at the Watertown Arsenal, and it was a practical process for specialized work. The Air Corps was considering it about the time we were considering it a few years ago, and at that time neither service was satisfied that it could be used with success on anything of the nature of welded joints. I hope it has been improved since.

With respect to photoelastic studies, Mr. Frosts' paper mentions and it is a fact that they were used to give a certain amount of confidence in the structure of the Shenandoah. I had something to do with another project for investigating the stresses in a landing gear structure. We were unable to secure any information from this of any practical value. I feel that the photoelastic method is one that eventually will be of great value, but I feel that experience with it should be built up on studies of important sub-assemblies, such as lugs, on which we now have what is practically only theoretical knowledge. The authors of texts on Strength of Materials should have information on photoelastic studies of sections around holes and the like. You will find in some advanced books on the subject that these things are discussed and that argument immediately arises between the man who uses the photoelastic method and the man who writes the book. I feel that until there is more agreement on the part of specialists in such matters engineers will not be able to make much use of it in our aircraft structures. Of course, for some bridges, dams, etc., the photoelastic method and the method of constructing a small-scale model and similar elastic studies, have been used; but I doubt the immediate applicability of any of these methods to aircraft without considerable practical experience which we do not now have. We would ordinarily be delighted to try any of these developments at the Naval Aircraft Factory, and whenever they are brought to our attention we do try them and give the industry the benefit of whatever experience we have.

METAL JOINTS IN AIRCRAFT CONSTRUCTION

MR. TEMPLIN.—In reference to the remarks made by Mr. Downes in his paper, regarding duralumin rivets, the larger aircraft which will require quite sizeable structural shapes are just around the corner, if not with us in a few instances. These larger structural shapes will necessarily require larger rivets, of duralumin we hope, and in the case of such rivets there is another procedure that can be used that we believe is superior in many cases to the scheme now used for driving these comparatively small rivets. In this other scheme which is now being regularly used in the case of structures made of duralumin, we simply heat up the rivets in a lead bath to the normal heat-treating temperature, and drive the rivets while they are hot. The result is that they drive very easily and the contact with the metal gives them the required quench so that we heat treat and drive rivets simultaneously with very satisfactory results.

MR. DIX.—Referring to Mr. Downes' paper, and particularly the section devoted to the soldering of aluminum, I thought I understood him, in his presentation of the paper, to refer to zinc-cadmium solder. I notice a reference in the paper to solder consisting of 12 per cent silicon and 88 per cent aluminum. It does not seem to me that that particular alloy should be considered as a solder; it is really a welding wire, although the usual welding wire composition is 5 per cent silicon. On the general subject of soldering aluminum in aircraft, it is not possible for me to conceive of an application where aluminum can be satisfactorily soldered. Mr. Downes refers to the disintegration of most aluminum soldered joints in contact with moisture and says if moisture is excluded, the condition of the joint will be unaffected by age, but except in a few rare instances where you might want to attach some little ornament or something of that sort with solder, I can hardly conceive of its use.

I think in connection with welding aluminum it may be well to mention the recent progress which is being made in electric welding. Mr. Downes has mentioned the electric spot welding. I should like also to tell you that electric butt welding and electric arc welding, both with the carbon arc and the metallic arc, are being developed to a point where they may be quite successfully used. With heat-treated aluminum alloys, they have the advantage, that is, all the electric welding methods have the advantage, of heating a much smaller area than the arc welding, and for that reason the structure is less affected.

MR. A. K. SEEMAN[1] (*presented in written form*).—In discussing the paper by Mr. Whittemore, I would again define a procedure control. It is a definite, detailed, particularized, and complete statement of:

1. Specifications for the material and apparatus used,
2. Ability of the operator,
3. Technique used in each operation, and
4. Inspection of the finished product.

Through application, procedure control methods have fully demonstrated that uniform high strength welds are obtainable, and that simplicity of design with attendant lowered welding costs accompany these high quality results.

In virtually every industry where metal is welded, procedure control has conclusively proved its benefits. The history of aviation is a striking example of the application of procedure control methods. Aircraft welding at the present time may be considered entirely satisfactory and the best method known at present for the fabrication of fuselages and certain other structural parts; but it is desirable that present practice be improved as much as possible, in order that even stronger, safer, more economical designs may result.

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[1] Aviation Service Division, Linde Air Products Co., New York City.

When the Bureau of Standards undertook the investigation of certain typical aircraft joints, one of its first problems was to produce uniform high-strength welds. The Bureau's welding experience on this type of work was decidedly limited. A correct method by which uniform welds could be obtained had to be found. A method for this particular investigation was furnished in the form of a procedure control, by a subcommittee of the American Bureau of Welding. The results of this application speak for themselves. Permit me to quote: "The test results show that the quality was uniformly good," and again: "In testing groups of three butt-welds made in the same tube, the strength of any one joint was in most cases found not to vary from the average for the three by more than 2 per cent although a different torch was used for each."

An industry somewhat analogous to aircraft, inasmuch as tubular members are welded together, is found in oil and gas pipe-line distribution. There are thousands of miles of gas-welded pipe lines in service in the United States alone. These lines must traverse all manner of country, over mountains, on the plains, under rivers, across deserts, under every climate condition. They must withstand the heat of summer and the cold of winter. Obviously, the welds are subjected to terrific strains. In most cases the welds are simple butt-welds. The fact that these lines are thoroughly dependable, requiring practically no attention, is but another illustration of the results obtained by procedure control methods which solved the welding problems of this particular industry.

The chemical industry, in which virtually all the welds are in heavy tension, is another instance where procedure control has been successfully applied.

Because welding, as applied to aircraft, started in a small way, and has but recently attained reasonably large proportions as a production process, its present state of perfection is decidedly remarkable. For some time, however, the welding industry has been keenly interested in the possibilities offered by aircraft production. Its engineers and metallurgists have been giving serious study to all phases of the subject.

The results of the investigation into the strength of welded aircraft joints recently concluded by the Bureau of Standards should very shortly be available to the public. The large suppliers of welding gases, apparatus, and supplies are busily engaged in many directions. Their metallurgists are bending their efforts toward the evolution of higher strength welding rod material susceptible of heat treatment. Already they have obtained encouraging results. Welding engineers are applying their skill and experience in the simplification of joint design which it is felt offers one of the most fruitful fields for future improvement. The aircraft industry has extended splendid cooperation in this work. Research into the technique of welding has been initiated both in the laboratory and the field. Aircraft metals have consistently improved and it is confidently felt that the laboratories of the metal manufacturer will produce still better metals. Improved methods of testing and inspecting welds are in the course of evolution.

Thus, with each of the several factors of a procedure control carefully considered we may in an orderly scientific manner improve aircraft welding practice to the end that the safety and prosperity of aviation may continue along the lines of its recent remarkable growth.

MR. BOULTON.—We have run across a problem recently in our aircraft construction that I should like a little light on. We have been recently making fittings of $\frac{1}{16}$-in. chromium-molybdenum steel sheet and heat treating it to 125,000 lb. per sq. in., and in a distressingly large number of cases have found a few hairline cracks which have been sufficient cause for rejection. If any one could throw any light on that problem or make any suggestions, I would appreciate it very much. We have been endeavoring to cut down our weight by going to the expense of heat treatment and getting the necessary strength with the heat treatment and the use of high-grade steels, but unless the procedure can be improved so as to eliminate that cracking, I am afraid it will prove too expensive.

MR. SOMERS.—We have had the same situation as Mr. Boulton in our plant, and we have overcome a good bit of the cracking by sand blasting the sheets before welding; we get a stronger weld; we do not get rid of all the cracks, but we get rid of 90 per cent of them.

MR. SEEMAN.—The cracking problem on chromium-molydenum tubing and fittings has been brought to my attention in several plants that I visited. An investigation which has not been completed indicates that most of the troubles can be eliminated by proper welding practices. In some cases it is necessary to heat the chromium-molybdenum sheet or tubing to a very dull red, which will relieve cold-working stresses that may be there. Sometimes this expedient does not suffice. The direction of welding oftentimes will cause cracking; welding away from an edge instead of towards it is one of the prolific sources of cracking. I think that the entire elimination of the cracking problem requires a study of the individual fitting that is being welded rather than a generalization on what constitutes the prime causes of cracks in chromium-molybdenum steel.

MR. CLAYTON.—The troubles that we have had in welding chromium-molybdenum are similar to those mentioned by Mr. Boulton and are partly explained by Mr. Seeman. Most of our welding trouble has been on the flat sides of square tubes, flat sheets, and the less curved portions of streamline tubes, round tubing being a lesser offender. Chromium-molybdenum steel in the normalized condition has a rated tensile strength of 95,000 lb. per sq. in. but always comes with a higher tensile strength than this. We have frequently received normalized chromium-molybdenum steel with tensile strength as high as 150,000 lb. per sq. in. but which fulfilled the physical and chemical specifications of S.A.E. No. 4130X steel. This steel with high physical properties has given considerable trouble in welding. It is our opinion that maximum permissible physical properties should be included in the specifications as well as minimum permissible properties. We believe that this would eliminate a great deal of the welding trouble.

MR. SOMERS.—I might add that we buy all our sheets in the annealed state and blank out the portions of the fitting, then normalize the fittings and sand blast them and then do the welding after that on an absolutely clean surface.

MR. BOULTON.—May I ask if the last speakers have heat treated their fittings after welding? We do not have much trouble if the fittings are not heat treated or normalized, but the difficulty seems to occur when they are heat treated to a reasonable value, say to 125,000 lb. per sq. in. tensile strength.

MR. SOMERS.—Yes, we heat treat them.

MR. CLEMENTS.—I think the cause of the cracking is not in the heat treating. It is true the cracks do not show themselves before the heat treating but they can be found if a careful examination is made. I do think the heat treating causes the cracks to grow. We often have trouble with new fittings and find by having the welder make some changes the cracks do not appear. We use all annealed sheets and heat treat after welding.

Some of the welding troubles with the high tensile strength tubing may be in the analysis. We sometimes have very thin walled tubing with all the hardening elements at the top limit which is subject to cracking more than some other lots. This cracking in high tensile strength tubing is probably caused by a different analysis.

MR. CLAYTON.—Actually the chemical analysis is within the requirements of the S.A.E. No. 4130X specifications.

MR. CLEMENTS.—Yes, but sometimes you may get the high limit on the chromium and carbon, and it is the air hardening that is causing some of the cracking.

MR. CLAYTON.—It seems to me that for welding purposes we ought to have maximum allowable physical properties as well as minimum allowable physical properties in our steel specifications.

MR. CLEMENTS.—I think there is no question that there should be an upper limit on the tensile strength. The requirement on elongation is supposed to take care of that but it does not do it all the time; sometimes we do get a lot of tubing that is up to 150,000 lb. per sq. in. tensile strength as received and no doubt there should be some upper limit on it, if you are going to cold work it without annealing. This hard tubing should be annealed before forming and then re-heat treated.

MR. SEEMAN.—I have conducted a simple test in several plants that I have visited where they have had cracking trouble with chromium-molybdenum tubing.

The physical condition of the tubing other than minimum specification requirements was unknown. A small piece of tubing perhaps ½ in. long was cut off with a hacksaw and then cut longitudinally. In every case where we investigated tubing that showed cracks we found heavy residual stresses in the tubing itself. The longitudinally split sections of tubing had either sprung apart or come together upon the release of these stresses. I have observed pieces of ¾ by 0.035-in. tubing spring ¼ in. A second piece of tubing was torch heated to a very dull red heat before cutting longitudinally. Subsequent longitudinal cutting showed the material to be free of stresses and welding showed no cracks. Chromium-molybdenum steel sheet exhibits similar characteristics.

MR. BOULTON.—I should like to ask whether it is considered that the thickness of the sheet, say down to approximately $\frac{1}{16}$ in., is considered one of the primary causes of cracking? We have had a considerable discussion in our plant as to whether it is practical to use sheets for fittings in gages as light as $\frac{1}{16}$ in., and there is a considerable opinion to the effect that we ought to go back to $\frac{3}{32}$ in. minimum.

MR. CLEMENTS.—We use large quantities of sheets which are less than $\frac{1}{16}$ in. and a large part of the tubing is less than $\frac{1}{16}$ in. About 0.035 in. thick is our minimum for welding the sheet. It is necessary to exercise more care in the welding of thin sheets than in the case of heavier sheets.

MR. BOULTON.—I was referring to sheet fittings.

MR. CLEMENTS.—We use sheet fittings $\frac{1}{16}$ in. and less in thickness. I think the thinner the sheet, the more difficult it is to make a weld without cracking. One-sixteenth inch may be the limit for a second class welder, but the best welder should not have trouble with this thickness.

MR. T. W. DOWNES.[1]—Referring to the comments by Mr. Templin, the method of heat treating duralumin rivets in lead is a new departure. It sounds interesting and I have no doubt that it may have possibilities. The only question which arises is that of corrosion. This has been the most troublesome thing in connection with riveted construction that we have encountered at the Naval Aircraft Factory, and it is generally conceded to be due to the rivets not having received thorough heat treatment.

In regard to the zinc-cadmium solder and the aluminum-silicon solder about which Mr. Dix spoke I might explain that it was not intended to mean that the zinc-cadmium solder had been used with aluminum. Perhaps this should have been put more properly under the head of special solders. The aluminum-silicon alloy containing 10 per cent of silicon is, possibly, not strictly a solder, but it is somewhat difficult to draw the dividing line.

Regarding spot welding duralumin, recent advances have been made in this art and the quality of welds produced has been very much improved.

I think the subject of cracking has been covered quite thoroughly and there is little or nothing that I can add.

HEAT TREATMENT

MR. CLAYTON.—I should like to ask Mr. Knerr what he considers the highest feasible value to which one could heat treat an aircraft structure. The tendency has been in the past to limit heat treating to 180,000 lb. per sq. in. I think we have reached the point where our technique is such that we can heat treat higher than this.

MR. KNERR.—Steel No. 4130X can be heat treated to 225,000 lb. per sq. in., and higher, without difficulty, but it is not always good design policy to figure on the maximum strength produceable. Such parts as heavy axles, which have to carry great loads for short periods can and are being designed as high as 200,000 lb. per sq. in. In wing beams or engine parts which are subject to fatigue, it does not seem wise to heat treat above about 150,000 or, in some cases, 175,000 lb. per sq. in., because both the yield point and the fatigue strength do not closely follow the tensile strength after this reaches, say, 175,000 lb. per sq. in. For structural members of very large craft (perhaps joined by means of bolts or rivets instead of welding) alloy steels of higher carbon content probably may be employed with safety to strengths as high as 300,000 lb. per sq. in.

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[1] Metallurgist, U. S. Naval Aircraft Factory, Philadelphia, Pa.

MR. WOODWARD.—On page 161, Mr. Knerr shows some tensile strengths and corresponding tempering temperatures for chromium-molybdenum steels. I know it is the practice of some aircraft concerns, I do not know just how many, to base all of their conceptions of tests as to heat treatment on tension test specimens which have accompanied the heat-treated parts. Now obviously due to the difference in the mass of the heat-treated samples and the tension test specimens, there is considerable difference in the properties obtained in the two. For instance, I am more familiar with the tension test specimens and know that the temperatures given would have to be increased quite considerably on the small tension test specimen to get the strength required. Could Mr. Knerr give us any information regarding that?

MR. KNERR.—Our own experience with the mass effect of aircraft structural members leads us to believe that it is not very great. In aircraft tubes whose thickness varies from $\frac{1}{4}$ in. to $\frac{1}{32}$ in. we have not found much difference between the tensile strength of the tube and the test strips cut from and heat treated with it. The elongation of the test strip is generally less than that of the tube. There is need for more information on this subject.

MR. WOODWARD.—We found there is a difference of three or four points on the Rockwell "C" scale hardness between the full size specimens and the tension test specimens; that would indicate that there would be some difference in the tensile strength also.

MR. KNERR.—With all due respect to the Rockwell hardness test, we have not found a close relation between Rockwell hardness and tensile strength in aircraft specimens.

THE CHAIRMAN (*Mr. Bradley Stoughton*).—I should like to ask Mr. Knerr if it is customary to heat treat duralumin parts after welding or riveting, either for annealing or other heat treatment, and if so, what size parts can be heat treated in that way?

MR. KNERR.—Very large duralumin parts cannot be heat treated in salt bath furnaces without danger of serious distortion. Duralumin is more apt to sag under its own weight during heating than steel. They can well be heat treated in electric furnaces, preferably having forced circulation of furnace atmosphere, and in which the work is suspended by wires from a rack or spider so as to avoid sagging. There is great danger of distorting large parts during quenching. Distortion is much less with oil than water. Air quenching avoids distortion and gives very nearly as good tensile properties as water quenching, and there is almost no limit to the size of parts which can be so handled.

Quenching duralumin in oil does not give quite as good resistance to corrosion as quenching in water, and the corrosion resistance of air-quenched duralumin is notably less, but for some purposes this does not matter. Alclad sheet probably will not show this variation in corrosion resistance with quenching and therefore could be quenched in oil or air without detriment.. Duralumin has the advantage of being soft, after quenching, so that it can be straightened, whereas steel parts are very difficult to straighten if warped in heat treatment.

THE NEW MANGANESE ALLOY STEELS

By E. E. Thum[1]

Synopsis

Contrary to the report that manganese should be held below one per cent in order to avoid brittleness in steel, the alloy is very strong and tough if carbon is reduced proportionately as the manganese is increased. Well over 250,000 tons a year of such medium-manganese steels are now used in the United States, and the following pages indicate the properties which have been developed in the various uses. In the as-rolled and normalized condition they are used for steel rails, high-strength structural steel, ship plate and boiler plate, seamless steel tubing, and compressed gas cylinders. In the heat-treated condition, medium-manganese steels (with or without another alloying element) find good use for such diversified parts as shock-resisting castings, high-test welding rods, carburized gears and machine parts, heat-treated forgings and press work, rifle barrels, leaf and helical springs, shear blades and non-deforming gages.

Manganese in any amounts beyond those incidental for the manufacture of sound metal has generally been frowned upon by users of high-grade steel. It was supposed to make them hard and brittle. Of course we had the well-known Hadfield's high-manganese castings (containing in the neighborhood of ten per cent of manganese), but the intermediate ranges have not been found in commercial steels until the last few years.

Former Ill Repute of Manganese

A brief account of how this useful alloying metal acquired its undeserved reputation gives the proper background.

The first attempts to make steel in a bessemer converter from English ores failed because the blown metal was wild in the ingot and could not be rolled, but Swedish pig iron, when used as raw material, gave immunity from these troubles. Robert Mushet found that the difference was due to manganese, and proposed adding a high-manganese pig iron (spiegeleisen) to blown metal to quiet it—a scheme which saved the new process, then quite discredited in England. It was rapidly found in practice that about 0.30 per cent residual manganese was necessary to remove oxygen or sulfur from the molten steel, or to locate them so as to be much less obnoxious to the finished metal.

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[1] Associate Editor, *The Iron Age*, New York City.

Since spiegeleisen is expensive, the steel maker attempts to use only a slight excess of this "medicine," and low-carbon plates, shapes and bars will seldom analyze more than 0.6 per cent manganese. The relation between manganese and carbon in the common tonnage steels now made in the United States by the basic open-hearth process is shown in Fig. 1, clearly illustrating this point.

Early and systematic researches indicated that medium-manganese steels were too brittle to work. This result was published by both Sir Robert Hadfield and by the metallurgists of Terre Noire works in France. It should be stated at once that these old results were correct. However, the only ferro-manganese available to make these alloys was high in carbon, and in putting in the required manganese an alliquot part of carbon was also introduced. The resultant brittleness was not due to manganese alone, as was inferred, but from the combination of manganese and carbon. "When manganese is up the carbon must come down" is the rule which has produced the successful medium-manganese steels of today.

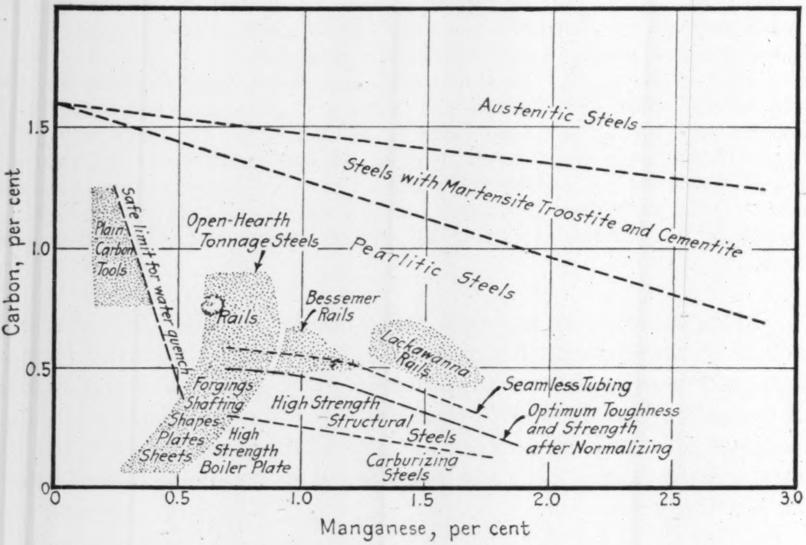

FIG. 1.—Showing Relation of Manganese and Carbon in Steel.

While plain carbon tool steels have a limited amount of manganese, the tonnage steels all contain 0.3 to 0.8 per cent. Material improvement in properties of plain carbon steel is gained by adding silicon, ordinarily less than 0.3 per cent for soundness, and from 1.0 to 1.75 per cent manganese for strength.

MANGANESE IN BESSEMER AND OPEN-HEARTH RAIL STEELS

An instance of how a carbon steel becomes a low-manganese alloy steel may be cited from the history of railroad rails. The first sizable consumption of bessemer steel was by railroads, and demand for a rail with harder wearing surface and stronger body grew with the increasing wheel loads. Harder steel meant higher carbon, and since bessemer steel was generally recarburized with spiegeleisen or a mixture of spiegeleisen and low-phosphorus pig iron, each increase in carbon meant correspondingly higher manganese. Manganese thus arrived in the rail specification through no recognized virtue of its own.

Railroad men, becoming convinced that phosphorus was the real embrittling element, began to demand open-hearth steel for heavy rails. More carbon was added to replace the hardening effect of the missing phosphorus, but there seemed to be some doubt about what to do with the manganese. Manganese remained high when open-hearth rail supplanted the bessemer, despite the fact that the carbon could be added in various ways without largely increasing the manganese content. More recent trends are shown by the following 1927 American Society for Testing Materials specifications:

	60-LB. SECTIONS	85-LB. SECTIONS	120 TO 140-LB. SECTIONS
Carbon, per cent	0.50 to 0.63	0.62 to 0.77	0.72 to 0.89
Manganese, per cent	0.60 to 0.90	0.60 to 0.90	0.50 to 0.90
Silicon,[a] per cent	more than 0.15	more than 0.15	more than 0.15

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[a] Opinion is favoring higher residual silicons in the carbon steel rails—0.20 per cent or more—enough to act as an effective gas solvent and to quiet the metal in the ingot mold. Such a sounder piping steel segregates less than when it partially effervesces, and segregated metal is found in most rails broken under traffic, and thus is more to be feared than an undiscovered remnant of the pipe.

A Real Alloy Rail:

Figure 1 shows plainly how the open-hearth rails rolled today are lower in manganese than the bessemer rails rolled prior to 1910. It also shows the chemical relationship of much higher manganese rails first used by the Lackawanna Railroad, and now being purchased by several American railroads at the rate of about 150,000 tons yearly. Its development is largely due to G. J. Ray, Chief Engineer, Delaware, Lackawanna and Western Railroad Co., after a study of the records of rails bought in the 1890's with those delivered during the war and later.

The older rails which gave so much satisfaction were rolled of bessemer steel in the plant of the Lackawanna Iron and Coal Co., located at Scranton, Pa. (now dismantled). Much of this old 80-lb. bessemer rail is still in service (1930) and has carried upward of 250 million tons of traffic, including locomotive wheel loads now thought more suitable for a 130-lb. section of open-hearth steel. While rail records were not so carefully kept and classified in 1893 as they are in 1930, a failure in these Scranton rails from a broken or split head was so rare as to excite comment. Transverse fissures were practically non-existent. In fact, the cumulative totals to January 31, 1928, from all railroads reporting to the American Railway Engineering Association show that rails made at Lackawanna's Scranton mill during the early '90's were practically immune from that defect.

A study indicated that the most obvious difference between these long-lived bessemer rails and the less reliable open-hearth ones of more "modern" manufacture was the fact that the former had low carbon and high manganese (carbon, 0.45 to 0.50 per cent and manganese 1.40 to 1.60 per cent). Consequently as a first approximation, the unique hardness and toughness (that is, low wear and few breakages) were ascribed to this peculiar chemical analysis. Study of records accumulated by the New York Central Railroad also showed that old heats having relatively low carbon and manganese as high as 1.30 per cent performed satisfactorily in track.

TABLE I.—TONNAGES OF MEDIUM-MANGANESE RAIL PURCHASED.

	TONNAGE REPORTED IN 1929	TONNAGE PREVIOUSLY REPORTED	TOTAL
Atchison, Topeka and Santa Fé	10 682	13 000	23 682
Boston and Maine	23 314	......	23 314
Chicago, Burlington and Quincy	29 150	58 700	87 850
Delaware, Lackawanna and Western	14 461	71 162	85 623
Louisville and Nashville	2 000	......	2 000
Northern Pacific	......	1 705	1 705
New York Central	65 390	83 250	148 640
Pennsylvania	......	942[a]	942
Reading	......	300[a]	300
Totals	147 947	229 059	377 006

[a] Experimental orders.

Some of the earlier rollings of this general type have not been satisfactory. But when the carbon and manganese are properly adjusted, excellent rails in every respect are produced, not only as judged by the inspector, but from performance records in track. Chemical analyses favored are:

	SECTION	CARBON, PER CENT	MANGANESE, PER CENT
Delaware, Lackawanna and Western	105 and 118 lb.	0.54 to 0.67	1.20 to 1.50
Delaware, Lackawanna and Western	130 lb.	0.57 to 0.70	1.20 to 1.50
New York Central	105, 115, 127 lb.	0.54 to 0.67	1.30 to 1.60

From first rollings in 1924, the use of medium-manganese rails has grown to the tonnages shown in Table I (preliminary figures by American Railways Engineering Association). Some roads are purchasing all their tonnage, and the New York Central buys approximately 40 per cent of its rails in this type of steel.

Practical experience in manufacture may be summarized thus:

1. No changes in the furnace practice for rail steel need to be made. The amount of recarburizer, ferro-manganese and ferro-silicon is slightly changed.

2. Quiet setting in the molds indicates a more complete deoxidation.

3. Rails discarded from pipe number 2.0 per cent as compared to 1.2 for a comparative tonnage of open-hearth steel, but this is more than counterbalanced by a lower percentage of second-quality rails.

4. Freer flow of steel in rolling is an advantage.

5. A finer grained structure is shown in specimens broken under drop test, and in microsections.

6. A cleaner steel is obtained, with decidedly less segregation. Chemical analyses in "O" and "M" positions on 210 heats of carbon rails gave carbon segregation of 8.3 per cent; 597 heats of medium-manganese rails gave carbon segregation of 5.1 per cent (both weighted averages).

7. Tensile and endurance properties, as determined by laboratory tests, indicate that medium-manganese rail has a shade the better of carbon steel. Deflection after the first blow of the drop hammer is slightly less and the average number of blows to break seems to be slightly greater. Hardness by ball indentation is a little greater, but the results cannot be translated into Brinell numbers. Other physical properties are:

	MEDIUM-MANGANESE STEEL	PLAIN CARBON STEEL
Tensile strength, lb. per sq. in.	122 000 to 138 000	111 000 to 128 000
Yield point, lb. per sq. in.	68 000 to 87 000	55 000 to 66 000
Elongation in 2 in., per cent	15 to 10	12 to 10
Reduction of area, per cent	32 to 17	20 to 12
Izod impact, ft-lb.	4.32	2.19

Undoubtedly superior performance in track has resulted. This evidence is best summarized in Fig. 2, representing composite sections of rails from groups which were laid adjacent to each other at the same time on the high side of a curve in heavy traffic territory. On tangent track, experience by the Lackawanna indicates wear of

0.0018 sq. in. per million tons as compared to 0.0045 sq. in. for standard open-hearth steel rail.

As to rail failures: 96 crushed and split heads have occurred from 1925 to 1929 in 171,430 gross tons of medium-manganese rail. A similar tonnage of standard carbon rails installed in track at the same dates could have been expected to develop approximately 230 failures (computed from American Railway Engineering Association averages). Records for transverse fissures are also excellent: six fissures in 170,000 tons, as compared to 14, as computed from the average performance of an equivalent life of carbon steel rails.

The net result indicates that the standard open-hearth carbon steel rail can be measurably improved by lowering the carbon to a range of 0.55 to 0.70 per cent and increasing the manganese to 1.25 to 1.50 per cent. Carbon and manganese both on the high side will be suspicious and probably brittle; both on the low side will give a rail which will probably flow under traffic. With the two elements properly balanced, a long-wearing, tough and generally satisfactory product is secured by usual good rail mill practice.

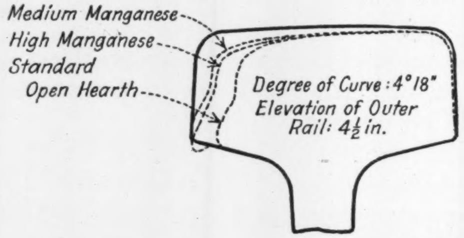

FIG. 2.—Comparative Wear of Rails Laid in Succession on the High Side of a Curve in Heavy Traffic Territory, Pittsburgh and Lake Erie Railroad.

The standard open-hearth rail was on the high side of the carbon range, the medium-manganese rail was within the limits specified for that grade of rails by the New York Central Lines, and the one marked "high manganese" was a rail from a special heat with manganese above the accepted maximum for experimental purposes. The latter is not to be confused with the so-called Manard rail, a Hadfield austenitic steel sometimes used where wear is excessive.

MANGANESE STRUCTURAL STEELS

High-Strength Carbon Steels for Structures and Ships:

Prior to the war the accepted method for getting extra strength in structural steel was to use an alloy steel in the as-rolled condition. The classic example is the chromium steel used by Eads in the St. Louis arch bridge in 1870, but this is unique as well as classic. American structural engineers have been in the habit of thinking of $3\frac{1}{2}$-per-cent nickel steel as their standard high-strength material, and it has been used satisfactorily in nearly every long-span bridge since the Queensborough Bridge in 1902. Only in comparatively recent years have they given serious attention to the possibilities of heat-treated carbon steels or low alloys of manganese or manganese and silicon, and here English and Continental engineers have led the way. In general, the low alloy steels are useful for moderately enhanced physical values, midway in properties and price between carbon steel and nickel structural steels.

In Great Britain the urge for inexpensive but better structural steels came from the Washington naval conference, limiting the weight of war vessels and consequently warranting a premium for steels with uniformly high proportional limits. Ship designers had previously gone on the assumption that the proportional limit of ship plate and shapes is one-half the tensile strength; when precise tests are actually made the proportional limit is found to vary widely, but the average is no more than 18,000 lb. per sq. in. Since the stresses in a ship's hull may be calculated with fair precision, and since these stresses should not cause permanent set in the frames, it follows that if a steel of uniformly high proportional limit could be produced, the actual limit of elasticity could be used for design purposes and much weight saved.

TABLE II.—CHEMICAL AND PHYSICAL PROPERTIES OF VARIOUS CARBON STRUCTURAL AND SHIP STEELS.

	English Mild Steel for Ships	Heat-Treated Carbon Steel Used in Holt's Ships	29 American Steels Not Responding to Heat Treatment	11 American Steels Responding to Heat Treatment	Heat-Treated American Steel
CHEMICAL ANALYSIS:					
Carbon, per cent..........	....	....	0.12 to 0.32	0.16 to 0.23	0.21
Manganese, per cent.......	....	....	0.34 to 0.64	0.51 to 0.77	0.64
Silicon, per cent..........	....	....	....	....	0.14
TENSILE PROPERTIES:					
Tensile strength, lb. per sq. in....................	65 000 average	72 000 average	60 400[a]	68 700[a]	83 100[b]
Yield point, lb. per sq. in..	33 000 average	....	40 300[a]	47 800[a]	66 500[b]
Elastic limit,[1] lb. per sq. in..................	9 000 minimum 31 000 maximum 19 000 average	33 000 minimum 45 000 maximum 37 000 average	....	....	....
Elongation in 8 in., per cent	20	20 to 30	25.9[a]	25.2[a]	18.5[b]

[a] Average value, as rolled; standard A.S.T.M. specimen.

[b] ½-in. specimens, quenched from 1600° F. and drawn at 1200° F.

[1] Routine determinations made by setting a Ewing extensometer at zero when the load is 4500 lb. per sq. in. The load is increased gradually to the minimum specified value of elastic limit and then reduced to 4500. Permanent extension must not exceed 0.0004 in. in 8 in.

As a matter of fact this improvement can be made merely by heat treatment, and has been done on higher carbon eyebars in America and more extensively on mild structural steels in Great Britain, in the form of a steel called "Martinel" or "Martin Elastic Limit Steel" after its proponent F. G. Martin, engineer for the shipping firm Alfred Holt and Co. Compare its properties with those of ordinary mild steel. The true elastic limit being so much higher (see Table II), a saving in dead weight of 10 to 14 per cent has been possible on several recent cargo vessels when the entire stress-carrying portion of the ship was made of heat-treated material. Main members in the arch bridge at Sydney (Australia) harbor are also made of heat-treated carbon steel.

It is worthy of note that studies on structural steels recently made by the United States Navy indicate that at least 0.20 per cent carbon and 0.60 per cent of manganese in a thoroughly deoxidized steel is necessary for response to heat treatments such as quenching from 1600 and drawing at 1200° F. Table II shows how this treatment enhances the strength and still retains enough toughness to bend $\frac{1}{4}$ and $\frac{1}{2}$-in. specimens flat without cracking.

TABLE III.—TESTS ON NORMALIZED STRUCTURAL PLATES.

	D-Quality for British Navy (as rolled)	Plates of Equal Strength		Plate Rolled at Low Finishing Temperature	Plates of Approximately Equal Carbon Content		
		High Manganese	High Carbon				
	1	2	3	4	5	6	7
CHEMICAL ANALYSIS:							
Carbon, per cent	0.33	0.29	0.50	......	0.18	0.23	0.22
Manganese, per cent	1.1 to 1.4	1.60	0.68	......	0.36	0.61	1.33
TENSILE PROPERTIES:							
Tensile strength, lb. per sq. in.	83 000 to 96 000	93 000	92 000	84 000	62 000	70 000	78 000
Yield point, lb. per sq. in.	56 000	53 000	48 500	55 000	32 000	40 000	47 000
Proportional Limit, lb. per sq. in.	Minimum 38 000 (Average 45 000)	40 500	29 000	51 500	18 000	22 500	36 000
Elongation in 2 in., per cent	17 (in 8 in.)	31	28	29	33	35	36
Reduction of Area, per cent	......	68	46	62	61	59	66
Endurance Limit (fatigue), lb. per sq. in.	......	45 500	40 000	34 000	29 000	36 000	40 000
Izod Impact	......	45	13	......	73	70	86
Brinell Hardness	......	183	186	......	126	140	156

Medium-Manganese Ship Steel ("D-Quality"):

Physical properties as good or better than those possessed by the above heat-treated carbon steels can be had in medium-manganese steels in the as-rolled condition. Such a steel containing carbon about 0.33 per cent, silicon about 0.12 per cent and manganese 1.1 to 1.4 per cent (known as "D" quality) is being produced with a minimum proportional limit of 38,000 lb. per sq. in., and an average of 45,000 lb. per sq. in. All portions of the hull contributing to the girder strength of British warships built in the last ten years have been of "D-steel," and no defects have developed in service.

D-quality steel is made of selected scrap and is cast in big-end-up molds with hot tops to feed the shrinkage cavity. Temperature and time of soaking is under control. Temperature at the final pass in the rolling mill is 1550 to 1620° F., rather above the critical range. Hot-bed cooling will then be equivalent to a normalizing treatment (that is, heated to 1560° F., and cooled in still air).

Physical properties are given in Table III, wherein proportional limits are determined with an accurate extensometer in the same manner as described in the footnote to Table II. Plates must also bend 180 deg. about a pin three times the thickness. D-quality steel fabricates somewhat less easily than mild steel, but shop men soon become acquainted with the material.

Data concerning the relative influence of carbon, manganese and cold work on structural steels are also shown in Table III. Comparison of column 2 with 3 indicates that it is better to get added strength by manganese than by carbon, because the proportional limit, ductility and especially the impact strength are better. High-carbon steel is also more sensitive to normalizing temperatures; if cooled from too low a heat a low proportional limit, yield point and tensile strength is found; too high a normalizing temperature reduces the already low impact strength. (I believe the only important American bridge using high-carbon structural steel—other than heat-treated eyebars—is the Hell Gate arch.)

High proportional limits may also be given to lower-carbon, lower-manganese steels by finishing them slightly below the transformation range. However, as column 4 of the table shows, this strengthening by cold work is at the expense of ductility and especially of fatigue properties. The last three columns of Table III indicate how the proportional limit in low-carbon steels is raised by manganese, even while the impact and ductility figures are slightly increased.

Air-hardening effects of manganese do not cause trouble in plates if manganese is less than 1.8 per cent in a 0.20-per-cent carbon steel, or less than 1.4 per cent in a 0.35-per-cent carbon steel (the limits shown by the dashed line marked "optimum toughness and strength" in Fig. 1.) Compositions above and beyond this line when normalized show increasing hardness and lowered proportional limit, ductility and impact strength. The dashed line may therefore be regarded as approximately marking the beginning of air hardening in $\frac{3}{8}$-in. plate.

Medium-Manganese Structural Steels in America:

While steels similar to the D-steel have recently been specified for a large American bridge, former practice has favored a so-called "structural silicon steel." This is really a misnomer, for as shown in Table IV the silicon is seldom over 0.30 per cent. Silicon is a strengthener, as is manganese, and consequently these steels have been called "silicon steels," even though their content is little if any greater than the residual silicon in an acid open-hearth steel. This definite excess makes for killed unsegregated steel, piped deep enough to require big-end-up ingots with hot tops, or else a discard up to 25 per cent from big-end-down ingots. As noted in the early part of this paper, strength is given to rail by high carbon and moderate manganese; the two are reversed in importance in the structural materials now under consideration.

It will be seen by comparing Tables IV and III that American engineers in their "silicon steels" prefer higher carbon and lower manganese than do the English constructors. Our chemical limits would run carbon 0.30 to 0.45 per cent, silicon 0.15 to 0.45 per cent and manganese 0.70 to 1.10 per cent. Such steel can be depended upon to carry 40 per cent greater load than carbon structural steel; it stands all the bending and drifting tests given the latter, and since it costs one cent or less per pound premium it is economical to use in large bridges where dead weight must be saved, in towers where high elastic limits are required, or in large structures where size and clearances are determining considerations. It is reported that the use of 8000 tons of high-strength steel in the 10,000-ton framework of the Richmond power station (Philadelphia) gave better column clearances at boilers and aisles, and lower heights, since smaller beams could be used or rolled shapes substituted for built-up girders. The estimated saving was $150,000.

TABLE IV.—AMERICAN HIGH-STRENGTH STRUCTURAL STEELS.

	Carbon Structural Steel, A.S.T.M. Specifications A 7	Metropolis Bridge, Ohio River (Modjeski, 1915)	Philadelphia-Camden Bridge, 1923	Richmond Power Station, Philadelphia, 1926	Towers for Hudson River Suspension Bridge, 1928	Kill van Kull Arch, 1929	British Steel Used in Mauretania, 1907	German "F" or Freund Steels
CHEMICAL ANALYSIS:	Approximate		Actual	Average	Average	Average		
Carbon, per cent	0.15 to 0.30	....	Maximum 0.44	0.35	0.35	0.33	0.27	0.13 to 0.17
Silicon, per cent	basic, less than 0.03	....	0.18 to 0.44	0.27	0.27	0.18	1.12	0.9 to 1.25
Manganese, per cent	0.40 to 0.70	....	Maximum 1.10	0.76	0.78	1.63	0.72	0.8 to 1.0
PHYSICAL PROPERTIES:		Specified	Specified	Actual	Actual	Actual		
Tensile strength, lb. per sq. in.	55 000 to 65 000	80 000 to 95 000	80 000 to 95 000	81 000 to 93 000	87 000	101 600	92 000 to 105 000	76 000 to 79 000
Yield point, lb. per sq. in.	Minimum 30 000	Minimum 45 000	Minimum 45 000	47 000 to 53 000	49 300	58 600	65 000	56 000
Reduction of area, per cent	....	Minimum 35	Minimum 35	46 to 36	42.1	42.6	....	...
Elongation in 2 in., per cent	Minimum 22	Minimum 17	20 to 17	24 to 18	21.6[a]	19.5[a]	25 to 30	24

[a] Elongation in 8 in. (mill tests.)

It will be noted that the steel in the main arch members of the Kill van Kull bridge (1675-ft. span) now under construction is of an analysis midway between the British D-steel and the American medium-manganese rail, and consequently has definitely eliminated silicon as an intentional strengthening element.[1] A 50-per-cent increase in strength in bridge columns made of this medium-manganese steel as compared with members of the same design built of ordinary carbon structural steel is proved by large scale tests made by the Port of New York Authority.

For these tests the 10,000,000-lb. testing machine at the Bureau of Standards, Washington, D. C., was used. Six columns were 24 ft. long, about 160 sq. in. in cross-section, and dimensionally one-half size specimens of the base columns of the towers of the Hudson River suspension bridge. Two others were dimensionally one-half size of a representative member of the lower chord of the Kill van Kull arch bridge. The six first mentioned were identical in size and make up, except that two were fabricated of ordinary structural steel, two of the so-called structural silicon steel as specified for the Hudson River bridge, and two of the new type of medium-manganese steel. The Kill van Kull specimens were of the third type, namely, medium-manganese steel.

TABLE V.—SUMMARY OF RESULTS ON BRIDGE COLUMNS.

Material	Dimensions of Column			Calculated Yield Points from Mill Tests, lb. per sq. in.	Column Test	
	Length, ft.	Area, sq. in.	Least Radius of Gyration, in.		Proportional Limit, lb. per sq. in.[b]	Stress at Failure, lb. per sq. in.[c]
HUDSON RIVER BRIDGE COLUMNS						
Carbon steel	24	159	9.97	40 200	17 000	33 600
Carbon steel	24	159	9.97	40 200	18 000	33 500
Silicon steel	24	159	9.97	54 900	22 000	52 800
Silicon steel	24	159	9.97	54 900	20 000	53 000
Manganese steel	24	155[a]	9.97	59 300	24 000	61 560
Manganese steel	24	155[a]	9.97	59 300	22 000	62 280
KILL VAN KULL BRIDGE CHORDS						
Manganese steel	20.75	144	10.51	59 600	24 000	59 000
Manganese steel	20.75	144	10.51	59 600	23 000	58 650

[a] Main webs reduced $\frac{1}{16}$ in. to keep column strength within capacity of testing machine.
[b] Determined from stress-strain curve.
[c] Stress at failure as understood in column testing procedure.

A summary of the results is given in Table V. It will be observed that the true elastic limit of the fabricated column (or at least that load where the linear relation between stress and strain undoubtedly ceases) is very much lower than the minimum yield point called for in the specifications for the steel. The latter figures are more nearly approximated by the stress at which failure as a column commenced. The slenderness ratios of these columns were relatively small, so there was no marked deflection of the column as a whole until ample evidence had developed that the column was at the point of failure.

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[1] It is a particularly attractive alloy to the steel makers because the scrap, either crop ends or off heats, may be remelted and converted into commercial grades of tonnage steel without necessity of segregation and conversion into special analysis alloy steel.

This completes the consideration of high-strength structural steels except to note the use of high-silicon steel in 1907 for the hulls of the Lusitania and Mauretania. The design did not prove so successful, however, and considerable metal was later added to decrease vibration. In the last few years a high-silicon steel has also been exploited in Germany under the name of "F" or "Freund" steel. Chemical compositions and physical tests are shown in Table IV. It is seen to be quite similar (except lower in carbon) to the special steel used twenty years ago in the Mauretania; exaggerated claims of high quality and low gas content due to manufacture at high temperature in a special furnace have been made.

HIGH-STRENGTH BOILER PLATE, TUBING AND GAS CYLINDERS

Boiler Plate:

In Fig. 1, an area of low-carbon steels below the structural grades is occupied by high-strength boiler plate and carburizing steels. The former is marketed in the United States as "silicon steel," although its ordinary chemical limits are carbon less than 0.35 per cent, silicon 0.20 to 0.30 per cent and manganese 0.60 to 0.90 per cent. This steel is used for high-pressure work, since its tensile strength of 70,000 to 83,000 lb. per sq. in. is at least 10,000 lb. per sq. in. more than can be had from commercial flange steel, and the elastic ratio (elastic limit divided by tensile strength) is about the same. Ductility (a minimum elongation of 22 per cent in 8 in.) is a little lower. It is produced and fabricated without difficulty.

High-strength plate is a matter of interest to the welding, chemical and petroleum industries, and experimentation on a large scale is in progress on the problem of seamless vessels to resist high pressures and temperature. For such service medium-manganese steels plus a little chromium offer good prospects. The following ranges have been investigated: carbon, 0.08 to 0.50 per cent; manganese, 0.60 to 1.80 per cent; and chromium, 0.30 to 1.10 per cent. A finer grain size, higher strength and satisfactory ductility is conferred by the chromium, either in the as-rolled or normalized condition. Steel of this type has also been used commercially for tubing.

Tubing:

High-strength tubing has been a noteworthy development during the last decade. Whereas lap-welded pipe, extra or double-extra strong, used to fill nearly every demand for unusual service, the increasing severity of specifications and the perfection of piercing machinery has enabled the manufacturers of seamless steel tubing to appropriate an increasing share of the business. Even in this form plain carbon steel is not good enough to withstand the stresses in the drill pipe used in deep oil and gas wells and medium-manganese steel has been substituted. With the deeper drilling to be expected, still higher strengths will be required, and can be met (together with the high ductility necessary) in an unheat-treated product only by higher manganese, or by introducing another suitable alloying element like the chromium mentioned above.

TABLE VI.—AIRCRAFT TUBING.

	Medium-Manganese Tubing (British)		Normalized Chromium-Molybdenum Tubing (American)
Specification	D.T.D. 89 A	D.T.D. 113	57–180–2A
Size of tubing	More than ½ in.	Less than ½ in.	all sizes
CHEMICAL ANALYSIS:			
Carbon, per cent	Maximum 0.30		0.25 to 0.35
Silicon, per cent	Maximum 0.30		......
Manganese, per cent	Maximum 1.50		0.40 to 0.60
Chromium, per cent	......		0.80 to 1.10
Molybdenum, per cent	......		0.15 to 0.25
MINIMUM PROPERTIES BEFORE WELDING:			
Tensile strength, lb. per sq. in.	100 800	78 400	95 000
Yield point, lb. per sq. in.	89 600	67 200	60 000
MINIMUM PROPERTIES AFTER WELDING:			
Tensile strength, lb. per sq. in.	67 200	67 200	80 000
Yield point, lb. per sq. in.	56 000	56 000	50 000

Manganese steel is used extensively in Great Britain for drawing into thin-walled tubing for aircraft fuselages, especially for members with welded joints, a service for which chromium-molybdenum tubing is used almost exclusively in the United States. Comparative specifications are given in Table VI.

Each type of tubing has its special advantages. British engineers prefer the medium-manganese steel on account of the higher yield points and the minimum tendency to air-harden at the weld, thus insuring good ductility even at the expense of strength. American engineers accept the air hardening after welding of the chromium-molybdenum tube as an advantage, enabling them to design fuselage members for higher unit stresses.

Gas Cylinders:

Cylinders for compressed gases may be regarded as a specialized application of seamless tubing. Such cylinders are made of steels whose composition is along the upper boundary of "high-strength structural steels" as dotted on Fig. 1. Most of those in use in America are so low in manganese that they fall within the range of tonnage steels, but a 0.5-per-cent carbon, 1.25-per-cent manganese steel has been marketed for many years. Recent trends are toward even higher manganese and lower carbons, in line with the principles stated at the beginning of this paper, and such an analysis (0.35 per cent carbon, 1.65 per cent manganese, 0.30 per cent silicon) has won recognition for its toughness. To meet the acceptance tests specified by the Interstate Commerce Commission, and still keep the weight of the cylinder within reasonable limits, steel with a tensile strength in the neighborhood of 100,000 lb. per sq. in. must be produced. Care in manufacture and testing has resulted in a practically perfect record of safety for the million or more high-pressure cylinders now in use.

RESPONSE OF MANGANESE STEELS TO HEAT TREATMENT

Manganese and iron are very similar chemically. In metallic alloys they form a continuous series of solid solutions: that is to say, manganese atoms are able to replace iron atoms in either gamma or alpha iron crystals with a minimum derangement in the space lattice. Probably because the elements are so alike, the speed of diffusion is unusually slow, and the cored crystals formed during solidification persist in later history. Special care to control pouring temperature and mold conditions is therefore necessary when making either ingots or castings. Heat treatments must be longer continued than for ordinary steels. Furthermore, high heatings do not unduly reduce the toughness, as would occur in plain carbon steels. Banded structures (sometimes called "fiber," the relic of cored crystals existing in the ingot) are frequently shown when forgings or rolled products containing more than 1 per cent of manganese are split and deeply pickled or etched.

A minor portion of the manganese forms a compound Mn_3C with carbon, analogous to cementite (Fe_3C). Some students of the subject believe that some double carbide $(Fe_3C)_3Mn_3C$ also exists, even in steels containing less than 1 per cent of manganese.

Increasing manganese lowers progressively the transformation temperatures in steels, especially on cooling. With 1 per cent manganese both Ar_3 and Ar_1 are lowered about 100° F. This means that the alloys may be furnace-cooled from the soaking heat to a temperature before quenching considerably lower than would be possible with a plain carbon steel. It also means that the drawing temperatures will be lower than for carbon steels. As above remarked, manganese renders the hardening reactions more sluggish than do other alloying elements which have an equal effect on the transformation range; hence the necessity for long times at heat. One per cent of manganese also shifts the eutectoid composition to 0.8 per cent carbon.

As a result of the above characteristics, normalized low-manganese alloy steels of the analyses shown in Fig. 3 tend to retain sorbite rather than to develop well-defined pearlite, and the amount of free ferrite after annealing is reduced. In normalized steels the grain size is also decreased, although in the as-rolled condition the microstructure is comparatively coarse.

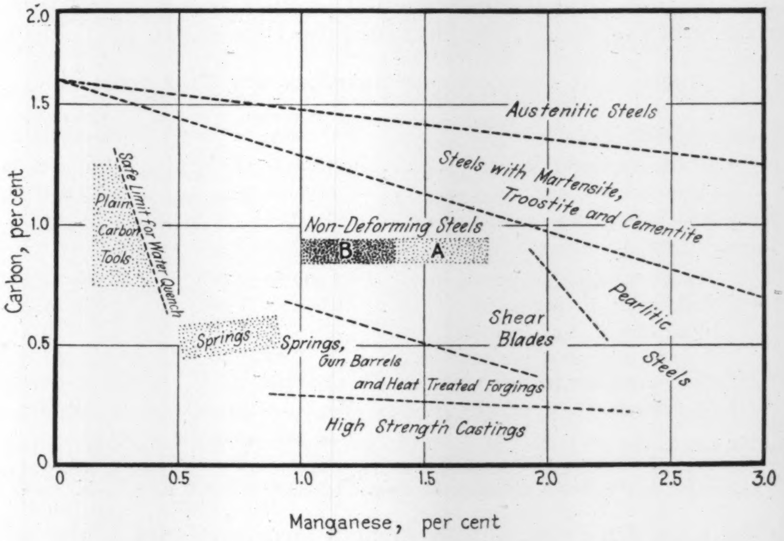

FIG. 3.—Low Manganese Steels Used After Special Heat Treatment.

High silicon or other alloy marked with double-hatching.

HIGH-STRENGTH CASTINGS AND WELDING ROD

Castings:

Lower carbons, with between 1.0 and 2.0 per cent manganese, give high-strength castings. These castings also have in the neighborhood of 0.30 per cent silicon, but since all bessemer and open-hearth steel for casting into sand molds is deoxidized with an excess of ferrosilicon, this residual analysis should probably be regarded as a characteristic of cast steel rather than warranting classification as a "silicon" alloy.

Cast steel containing 1.25 per cent of manganese was developed by Henry Marion Howe and John Howe Hall, and first made commercially in America in 1909 into dredge buckets and bucket teeth, in response to a demand for material that would wear longer and break more seldom than plain carbon steel castings. Comparative physical properties are shown in Table VII. It will be noticed that the carbon steel casting, by virtue of high carbon and a special heat treatment has been given unusually high properties; nevertheless a steel with higher manganese and lower carbon, properly heat treated, has a notably increased yield point, toughness and impact strength. Furthermore (as in normalized structural steels), the yield point is sharply defined in manganese-bearing castings, which is not true of carbon-steel castings. The physical properties shown in Table VII almost approach those of high-strength structural steel in the rolled and normalized condition, but represent the normal tests on this material when properly made.

TABLE VII.—PROPERTIES OF HIGH-STRENGTH CAST STEELS.

	CARBON STEEL	1.25-PER-CENT MANGANESE STEEL
CHEMICAL ANALYSIS:		
Carbon, per cent	0.45 to 0.55	0.20 to 0.30
Manganese, per cent	0.60 to 0.80	1.10 to 1.40
Heat treatment	[a]	[b]
PHYSICAL PROPERTIES:		
Tensile strength, lb. per sq. in.	82 000 to 92 000	80 000 to 90 000
Yield point, lb. per sq. in.	46 000 to 51 000	52 000 to 57 000
Elongation in 2 in., per cent	20	28
Reduction of area, per cent	25	55
Charpy impact, ft-lb	10	32
Microstructure	Very fine pearlite and ferrite	Sorbitic

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[a] Heated at 1650° F. for 5 hours, colled in air, reheated to 1250° F. for 8¾ hours, cooled in air.

[b] Heated at 1650° F. for 5 hours, quenched in water, reheated to 1200° F. for 6½ hours, colled in air.

For these reasons 1 to 2-per-cent manganese-steel castings were largely used in ordnance during the war, and now are made into car-coupler knuckles, locomotive, truck and tractor parts where an especially high-grade casting is required. An interesting application of 0.35 per cent carbon, 1.35 per cent manganese is for cast-steel anchor chain; besides its strength and toughness it resists sea-water corrosion excellently. This is probably due to the very fine grain size of the sorbitic structure and the lack of free ferrite, rather than to any intrinsic characteristic of the manganese.

Locomotive frames and other large castings have been made of such steels, to which chromium has been added. Representative analyses are carbon 0.35 to 0.40 per cent, manganese 1.40 per cent, chromium 0.60 to 0.70 per cent. Physical properties achieved after very careful heat treatments are 110,000 lb. per sq. in. tensile strength, 65,000 lb. per sq. in. yield point, 18 per cent elongation in 2 in., and 24 per cent reduction of area.

Welding Rod:

While welding rod is not a heat-treated material, a brief note here is not out of place because a first-class fusion weld is in the nature of a high-strength casting. A second reason is that a much used proprietary material contains high manganese and silicon, as shown in the last column of Table VIII.

Comparison of the analyses both before and after having been melted (as by the oxyacetylene flame) shows that carbon burns out unless protected by a surplus of manganese or silicon. For that reason the probable strength of a weld made by a good workman with so-called Norway iron rod will be only 47,000 lb. per sq. in., whereas 58,000 lb. per sq. in. may reasonably be expected from joints made with the "high test" rods.

TABLE VIII.—COMPOSITION OF WELDING RODS AND RESULTING WELD METAL.

	"NORWAY IRON" WELDING ROD	MILD STEEL	"HIGH TEST"
Carbon, per cent	0.05	0.25	0.20
Manganese, per cent	0.15	0.45	0.80
Silicon, per cent	0.01	0.02	0.55
COMPOSITION OF WELD METAL			
Carbon, per cent	0.03	0.08	0.18
Manganese, per cent	0.07	0.20	0.48
Silicon, per cent	0.01	0.01	0.25

MANGANESE STEELS FOR CARBURIZING

Steels for case-hardening purposes, as purchased in America, have ordinarily been specified with low manganese, probably on the theory that the surface will be converted into a high-carbon steel, and this should have restricted manganese in order to avoid cracking when water quenched. On the other hand, British practice permits 0.70 and even 0.90 per cent manganese; it gives a sound hard case, and a tougher, stiffer core. The general excellence of such steels with a moderate amount of manganese for case hardening,—that is, uniform carburization, tough cores, and uniform hardness,—warrants much more attention from American users.

A special carburizing steel (S.A.E. No. 1315X) is now on the market under the trade-name "Jalcase" which carries this matter even further to a steel for oil hardening. Its chemical limits are carbon 0.10 to 0.20 per cent, sulfur 0.08 to 0.13 per cent, and manganese 1.25 to 1.75 per cent. The cores of 1½-in. bars of this material after double heat treatment can have Izod impact values over 90 ft-lb. Higher manganese reduces the chance that the steel may be "abnormal" and develop soft spots after case hardening. Sulfur in this analysis is high enough for easy cutting in screw-machine products; the high manganese also counteracts the brittleness to be expected from unduly high sulfur. A free cutting, tough, and "normal" steel is a rather remarkable combination of properties.

A most interesting recent development in steels for case carburizing is a medium-manganese steel which has a little molybdenum added to the chemical analysis. This has the well-known effect of reducing the "mass effect," that is, reducing the difference in properties, surface to center, of a heat-treated piece. It has been established that 0.25 per cent of molybdenum will improve the Izod impact values (representing toughness) of medium-manganese steel at least 10 per cent, a change associated with a fine grained microstructure after carburization in the McQuaid-Ehn test. Molybdenum also appears to improve the uniformity of response to heat treatment, decreasing the number of rejects beyond specification limits when a medium-manganese steel without molybdenum is carburized.

Medium-manganese steels with molybdenum carburize about 75 per cent deeper in a given time than the nickel-molybdenum steels (S.A.E. No. 4615) Flexural strength of hardened bars is about the same, but the impact strength of the case-hardened and heat-treated Izod bars is much inferior. Vickers hardness of the steel, oil-quenched from the pot, is 715, and this hardness is maintained to a depth of 0.035 in.

Such characteristics indicate this steel to be useful for inexpensive gears, for instance, where the load is steady and not severe, and where lubrication may at times be deficient.

QUENCHED-AND-TEMPERED FORGINGS

A fairly wide range in carbon steels containing more manganese than the normal have proved suitable for heat-treated parts. Most of it sold in America is along the lower boundary of the area shown in Fig. 3, and contains from 0.30 to 0.50 per cent carbon and 1.0 to 2.0 per cent manganese. Steels of this grade are becoming more popular as an easy working steel of moderate price, with enhanced properties after heat treatment midway between plain carbon steels and the chromium-nickel steels.

Unsatisfactory experiences with heavy forgings within the upper limits of this range have been reported; the steel was found to be segregated, to contain too many silicate inclusions, and a coarse structure (large grains of pearlite) which could be refined only with great difficulty. Probably such steel was cast too hot and before the refining reactions had been completed; the solidified ingot then had large crystals separated by slag particles, the latter in turn interfering with subsequent grain refinement and causing "ghost lines," "streaks" and other defects encountered in large forgings. It is now generally recognized by steel makers that manganese steels require "alloy quality" rather than "tonnage practice," especially when the manganese exceeds 1.75 per cent; when the forging shop practice is correspondingly careful, it has been demonstrated that such steels forge well into difficult shapes and are preferable to other analyses capable of developing similar physical properties.

Manganese steels, while tending toward air-hardening, do not harden deeply. The characteristic condition in a quenched 5-in. round after tempering at 900° F. would be a good impact value at the center (Izod, 45 to 65 ft-lb.), but an elastic limit lower than would be expected in small test pieces of equal hardness. If deep hardening is an essential, a little molybdenum should be added to the analysis.

Carbon and manganese should vary inversely along the upper boundary of the useful area shown in Fig. 3. It has been stated that for forging steels carbon should be less than 0.30 per cent if manganese is about 1.75, but since steels with 10 points more carbon have been successfully used for automobile axles, the first-mentioned carbon limit is too conservative. The following comparison with other steels, heat-treated to medium tensile strength, shows that these manganese steels are closer kin to alloy steels than they are to carbon steels:

PLAIN AND ALLOY STEELS HEAT TREATED TO 135,000 LB. PER SQ. IN. TENSILE STRENGTH.

CHEMICAL ANALYSIS:	CARBON STEEL	MEDIUM-MANGANESE STEEL	MEDIUM-MANGANESE STEEL	NICKEL STEEL
Carbon, per cent	0.55	0.51	0.34	....
Manganese, per cent	....	1.35	1.38	....
Nickel, per cent	....	....	....	3.61
PHYSICAL PROPERTIES:				
Proportional limit lb. per sq. in.	93 000	117 000	114 000	126 000
Elongation in 2 in., per cent	18	20	17	21
Reduction of area, per cent	51	53	57	59
Izod impact value, ft-lb.	14	58	68	65

It must be remembered that the impact strength of manganese steel is not as good as that of the nickel and chromium-alloy steels when heat treated to high tensile strength, say 200,000 lb. per sq. in.; in other words, manganese steels are most useful in the intermediate ranges where a high value of the true elastic limit is desirable.

Drop forgings, axle shafts, steering parts, high-duty bolts and studs for automobiles are being extensively made of manganese steels, either basic, open-hearth or electric. Specification and average properties of the material known as "G.M.C. 1335" in 1-in. bars are as follows:

	SPECIFICATION	AVERAGE OF 51 OPEN-HEARTH HEATS
CHEMICAL ANALYSIS:		
Carbon, per cent	0.30 to 0.40	0.35
Manganese, per cent	1.60 to 1.90	1.77
Silicon, per cent	0.15 to 0.30	....
PHYSICAL PROPERTIES:		
Tensile strength, lb. per sq. in.	140 000	162 500[a]
Yield point, lb. per sq. in.	125 000	152 500[a]
Elongation in 2 in., per cent	15	15.8[a]
Reduction of area, per cent	50	55[a]

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[a] After water quenching from 1550° F. and tempering at 900° F.

A somewhat lower alloy is used for pressed steel frames for auto-busses and trucks. These are made of steel plate containing 0.25 to 0.35 per cent carbon, and 1.30 to 1.60 per cent manganese. Average physical properties of the finished frames are:

Tensile strength, lb. per sq. in.	115 000
Yield point, lb. per sq. in.	100 000
Elongation in 2 in., per cent	35
Reduction of area, per cent	50
Brinell hardness	255 to 302

It is reported that such frames resist the shocks of over 500,000 miles of road service much better than plain or heat-treated carbon steel, owing to their high strength, ductility and endurance limit.

SPRINGS

While the bulk of the small steel springs used in industry are made of cold-drawn music wire, or heat-treated high-carbon steel wire or strip, many varieties of the larger springs also contain considerable manganese. "Tempered wire" with 0.60 per cent carbon and 1.15 per cent manganese is widely used for coils by mattress and upholstered furniture manufacturers. Gun recoil springs for smallcaliber naval ordnance are made of about the same analysis; helical springs made of $\frac{3}{4}$-in. round rod, oil-quenched and drawn, have withstood severe proof tests, and behave well in service.

The stippled area marked "springs" on Fig. 3, represents silicon-manganese steels used principally for vehicle leaf springs. If received from the mill with Brinell hardness less than 300 it can be sheared and punched cold. Typical analyses are as follows:

CHEMICAL ANALYSIS:	S.A.E. No. 9250	S.A.E. No. 9260
Carbon, per cent	0.45 to 0.55	0.55 to 0.65
Silicon, per cent	1.8 to 2.2	0.8 to 2.2
Manganese, per cent	0.6 to 0.9	0.6 to 0.9

Silicon and manganese in these analyses permit a wider temperature range in forming and hardening than can be used when working with plain high-carbon steels, but even the silico-manganese steel is more sensitive to variations in heat treatment than some of the other alloys like chromium-vanadium steel used for leaf springs. While the number of analyses of springs used in America about equals the number of models of motor cars current, the silico-manganese grades are favored in America principally by factories which have accurate temperature control and orders for very large quantities. Here again the quality is intermediate between carbon steel and more expensive alloys; the manganese is valuable to prevent excessive scaling and to insure against large grain growth if overheated. Materials of this general analysis used in France are so much lower in manganese as to warrant classifying them as silicon steels.

Silicon-manganese steels have also been made into helical springs for electric locomotive drives, railroad rolling stock, and other severe duties.

SHEAR BLADES AND SMALL-DEFORMING STEELS

A considerable area on Fig. 3 represents compositions suitable for shear blades for cold-cutting iron bars and scrap. Steel with as high as 0.80 per cent carbon and 2.0 per cent manganese can be successfully hardened in masses weighing 500 lb. After oil quenching and tempering, these comparatively cheap steels will give as good or better service than a chromium or chromium-vanadium steel with the same carbon content.

"Non-deforming" or "non-shrinking" steels as originally proposed by John A. Mathews contain 0.80 to 0.95 per cent carbon and 1.5 to 1.75 per cent manganese. About 0.5 per cent manganese was later replaced by an equal amount of chromium, with sometimes 0.5

per cent of tungsten as well. Any of these analyses may contain a little vanadium to advantage. The more complex alloys, although more expensive in raw cost, are somewhat easier to make and forge, and to machine when in the annealed condition.

The name is something of a misnomer. It should be "small-deforming." All the steels *do* change in volume slightly during heat treatment, but the changes are slight, and the heat treatment can be so selected that the principal dimensions after hardening will be almost exactly the same as before. Consequently these steels are favored for plug and thread gages, delicate stamping dies, master tools, hobs, taps and broaches, and flat surfaces.

Study of the volume changes indicates that non-deforming steels retain a considerable quantity of untransformed austenite after the oil quench, scattered about in the bulk of the martensite. The latter progressively decomposes into troostite at temperatures beginning at 200° F., and this change causes a contraction in volume. After reaching 500° F. the retained austenite transforms to martensite and expands, this entire change taking place within a narrow range; above 550° F. this secondary martensite also tempers (and contracts). Small volume change requires a heat-treatment schedule such that these contractions and expansions cancel each other. Owing to the preponderating amount of martensite present at all times, the surface hardness is substantially constant for all draws below 600° F.

Acknowledgment:

In conclusion, the author wishes to confer his indebtedness to a very numerous body of friends; from each has been gleaned one or more items of information on these new steels, nearly all of it unpublished. Those contributing especially generously are G. J. Ray and C. B. Bronson on rails; O. H. Ammann, J. A. Jones, and Lieut. P. F. Lee on high-strength structural steels; J. H. Hall on medium-manganese castings; and C. E. MacQuigg, Jerome Strauss and T. W. Hardy on analyses suitable for heat treating.

DISCUSSION

Mr. Bradley Stoughton.[1]—I want to corrected one impression which I think perhaps Mr. Thum gave unintentionally: The high manganese (about 1.10 per cent) which we used to have in the old bessemer rails was not accidental. We put in a lot of spiegeleisen, but it was intentional. The railroads demanded the high manganese in these rails because it made the heads more durable against abrasion.

I want to ask Mr. Thum whether, in the microstructure of these medium-manganese steels, he does not find that they are sorbitic rather than pearlitic? We examined some of these for the steel in the Kill van Kull bridge, and it struck us that, in the first place, the microstructure was very, very coarse; there were enormous great crystals which I understand is typical of these steels; but in the second place, it seemed to be sorbitic rather than pearlitic in structure, and I tentatively attributed the high strength to this sorbitic structure. I do not know whether any other explanation has ever been offered for the strength of these manganese steels, but perhaps Mr. Thum can tell us about that also.

Mr. H. H. Morgan.[2]—I think that the idea conveyed by Mr. Thum's paper is that here is a steel with which we can go as far as we want—that there is no limit to the uses to which this steel can be put. This is not true. The analysis of intermediate manganese steel must be carefully studied in reference to the service conditions. As an illustration of this, I want to speak of intermediate manganese rail steel where we have conditions of wear resistance, safety, and resistance to severe stresses to consider.

The increase in manganese over carbon rail steel gives greater wear resistance but the carbon must be reduced to meet safety conditions. The reduction in carbon is a distinct advantage as rail steel is not heat treated. Even under this condition, we have found some trouble with intermediate manganese rail steel. In an occasional heat of this rail steel, not a high percentage, but in an occasional heat where the carbon and manganese are toward the upper range of the usual rail specifications for this steel we find a peculiar condition. This condition exists in occasional heats that have carbon from 0.65 to 0.70 per cent and up around 1.55 to 1.60 per cent manganese or occasionally higher. In a percentage of the cross-section of the rail representing undoubtedly what was originally the center of the ingot, we find a zone of material that shows a peculiar condition. There are streaks of martensite in the form of needles extending longitudinally. These needles are from 1 to 2 in. long and of a diameter smaller than the finest sewing needles. We cannot always count them but there may be a few or there may be a hundred. These small martensite areas are imbedded in lamellar pearlite. Now when these odd heats in a railroad track are subjected to unusual stress, such as the inside rail of a curve under slow-speed freight traffic, the stress may be sufficient to produce strains down in the zone of these martensite needles. Under strain the martensite needles will naturally break and a split head commences to develop.

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[2] Manager, Rail and Fastenings Department, Robert W. Hunt Co., Chicago, Ill.

I have mentioned this condition as a matter of fact, simply to indicate that there may be conditions develop in the use of this steel that would suggest the wisdom of studying the matter of analysis very carefully before adopting the intermediate manganese steel for some particular service.

While we have not arrived at a definite conclusion as yet as to the reason for these martensite needles and how we are going to correct the condition, it is possible that the line of eutectoid will run much lower than is implied in the diagram of Fig. 1 of Mr. Thum's paper. We think likely that in the diagram of Fig. 1 the eutectoid line would start at 0.9 per cent carbon for 0 per cent manganese and run at a slope to about 0.6 per cent carbon for 2.0 per cent manganese.

In closing, I want to say that we should be careful not to get the impression that we can do anything we want with this steel.

MR. L. S. MOISSEIFF.[1]—I wish to make a correction in the table given by Mr. Thum for the Hudson and the Kill van Kull bridges. The Hudson River Bridge contains in its towers and in its entire structure no manganese steel at all. It is built of carbon and silicon steel. The columns of carbon-manganese steel tested at the Bureau of Standards given in the table have been added later to obtain a comparison of the same type of column for carbon, silicon and manganese steels. The Kill van Kull bridge was originally designed and contracted for nickel steel in the main rib and silicon steel in the rest of the arch frame. At the request of the American Bridge Co., carbon-manganese steel was permitted to replace the nickel steel. As no column tests of manganese steel were available, such were added to the series of tests made by the Port of New York Authority jointly with the Bureau of Standards. To connect the behavior of one form of column to the other, a manganese-steel column of the Kill van Kull type was added to the Hudson River bridge schedule. I believe that in time the Port of New York Authority will publish all its data and experience with the carbon-manganese steel used in the Kill van Kull bridge.

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[1] Consulting Engineer, New York City.

The results of the tests of the large size columns show that the column strength of a well-built column is practically its yield point. You will find that the yield point of the silicon steel used in the column tests and that of the carbon-manganese steel are not very different. They vary from 54,000 to 59,000 lb. per sq. in. A doubt thus arises in the mind of the designer, why go to a steel that is as yet in its making? A steel that carries with it at least a number of growing pains? When the gain in yield point and column strength is only 54,000 to 59,000 or 60,000 lb., why is it worth the troubles of substitution? Bridge specifications for silicon steel call for a minimum yield point of 45,000 lb. and an average of 47,000 lb. per sq. in. is called for in the Hudson River bridge. It seems to the speaker that if the yield point of silicon steel could be raised, there would be no need to go to more difficult steels. Carbon-manganese steel, I would add, is as yet a steel in the making. When good, it works well. When doubtful at times, it shows a number of faults; it develops cracks and requires careful handling. It cannot stand flame cutting and I might add that its action in tension members is not quite verified.

MR. R. S. JOHNSTON.[1]—I happen to have been connected with the column tests mentioned and want to call attention to the fact that the columns of silicon steel Mr. Moisseiff spoke of had a high average yield point on the curves, because it happened that the thin angles we had to have rolled to get dimensional conditions ran very high in yield point, rather higher than the average for structural silicon steel. That brought the average yield point of those columns up rather high.

MR. E. E. THUM.[2]—Mr. Stoughton answered his own question regarding the structure of medium-manganese steel. The text of the paper on page 228 has some remarks about the micro-structure, fiber and other such features, commonly observed in medium-manganese steel. Also in the section wherein steel castings are discussed are some other remarks upon the desirability and necessity for very thorough heat treatment.

Mr. Morgan pointed out that the medium-manganese steel rail is probably not the ideal rail. I believe no one would hold that they are immune from troubles in the track. As far as I know there has as yet been found no cure for transverse fissures caused by the present high wheel loads and fast traffic. In the present state of our knowledge, the best way to avoid the martensitic centers in the rails observed by Mr. Morgan is to be sure that the carbon and manganese in the rails shall not both reach the high limit.

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[1] Director of Research, John A. Roebling's Sons Co., Trenton, N. J.

[2] Associate Editor, *The Iron Age*, New York City.

I am sorry if my paper leaves the impression that medium-manganese steels are being used in the Hudson River suspension bridge. I have presented data on a number of steels other than medium and manganese steels simply in order that comparison may be made. Data will be found in the text on heat-treated carbon steels, "structural silicon steels" and similar steels in Table IV; in other words, the paper contains data on a number of steels which are not to be classed as medium-manganese steels, merely for the purpose of ready comparison.

THE RELATIVE MERITS OF SOME DIFFERENT ALLOY STEELS WITH RESPECT TO CERTAIN MECHANICAL PROPERTIES

By Bradley Stoughton[1] and Wilber E. Harvey[2]

Synopsis

Taking as a basis about fifty binary or ternary alloy steels whose chemical analysis and mechanical properties have been published, about 1800 numerical calculations were made grading these steels in order of their relative standing according to the numerical value of the product of some function of their strength multiplied by a function of their ductility or according to values of strength multiplied by Izod impact value. Up to this point the work was intended merely as a research into properties of the different types of steel and methods of comparing those properties.

Only a few steels were chosen: namely, nickel, chromium, chromium-nickel, chromium-vanadium, chromium-molybdenum, medium-manganese and silico-manganese. The reason for starting in such a small way was because the work was so time-consuming, and because the number of different factors which have to be taken into consideration in grading the qualities of steels was so large, that a better start could be made by limiting the number of types and the extent of the field of application, in order to present a classification for discussion purposes. A preliminary discussion of the results has been presented in the hope that this will lead to constructive criticism, suggestions and further data for comparison. Upon the extent of these criticisms and offerings will depend the lasting value of the work presented.

In the metallurgical world the most important innovation of the present century has been the increasing production of alloy steels, until their output is on a substantial tonnage basis of more than three million tons per year in the United States alone. This is due very largely, of course, to the automobile industry, which is the largest consumer of steel in the United States (taking the last two years together) and which uses more than three-fourths of all the alloy steels. Twenty years ago, less than one per cent of our steel production was alloy steel, whereas today it is more than 6 per cent. This rapid growth is confined chiefly to the last 15 years, notwithstanding that several alloy steels were old in industry before the beginning of this century. After much discussion, pro and con, it seems to be established that Eads *did* use chromium steel in the St. Louis bridge in 1873 for its structural advantages. Hadfield discovered his manganese steel in 1882, and his equally famous silicon transformer steel in 1883 and 1884.[1] It is estimated that the use of these two steels has saved the industrial world more than two billion dollars to date. James Riley, in 1889**(10)**,[2] was the first to bring emphatically to public notice the value of nickel steels, and the monumental book by Howe**(11)** of the same year gives data on additional alloy steels: namely, tungsten, copper, titanium, vanadium, molybdenum, and aluminum.

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[2] Instructor, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

Hadfield divides the new era of alloy steels into the following periods:[1] 1880 to 1895, 1896 to 1914, and 1915 to date. During this last period the production and consumption of alloy steels has been growing amain. Not only the tonnage of old types, but also the number and tonnage of new types have greatly increased. Fortunately the several varieties of binary and ternary steels usually suffice for resistance to simple static, dynamic (that is, vibratory, alternating or fatigue) and impact strains. These are the steels considered in this study. Where the problem is complicated by an additional requirement of hardness, resistance to heat, electrical or magnetic characteristics, quarternary steels are often necessary. But even the relative advantages in service of alloy steels of different analysis, under the three types of simple stress mentioned above, are still very much in doubt. It has, therefore, seemed to us important that a start should be made in classifying our available knowledge on the subject and attempting to bring some sort of order out of chaos. We are aware of the limited field studied, such as the small number of alloy types included, and the very few impact tests found. One of the chief reasons for the paucity of impact tests is that so few tests have been published and also because different observers perform the impact tests by so many different methods that correlation is often impossible.

QUALITY FACTORS AND WORTH

If steel is to resist structural strains, the two most important properties it should have are strength and ductility, because resistance to static, dynamic and impact strains is made up of combinations of these two. By structural strains we mean the strains which come in service on the structural members of buildings, bridges, vehicles and machines. In some of these members strength is more important than ductility, and *vice versa*. The ideal way to evaluate the worth of an alloy steel for any service would be to assign the best relative factor to each of these two properties (if we could determine it), multiply the strength by its factor, the ductility by its factor, and then multiply the two products together. The highest figure obtained in this way would represent the best steel for the service in question. One of the difficulties with this procedure is that we have no definite measure of the ductility. The elongation in 8 in., the elongation in 2 in., and the reduction of area in tension tests are all indications of ductility. The bend test and drop test give additional indications.

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[1] Private communication, March 13, 1930.

[2] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended hereto.

A. B. Kinzel(9) has published a method of studying and interrelating these properties in order to express quantitatively the technical worth of a steel.

Quality Factors:

Attempts have been made to establish so-called "quality factors" which shall represent in a general way the value of a steel for structural purposes. The quality factor which has probably been most used in this connection is the tensile strength multiplied by the elongation in 2 in. This is as simple a quality factor as could be devised but is considered by many to be too rough for general application. In our summary we shall show how this quality factor compares with others. We have called this quality factor "A."

Other quality factors which have been or might be suggested are the following:

Quality Factor "B" = Elastic Limit × Reduction of Area
" " "C" = Elastic Limit × Elongation in 2 in.
" " "D" = Elastic Limit × Elongation in 2 in. × Reduction of Area
" " "E" = Elastic Limit × $\sqrt{\text{Elongation in 2 in.} \times \text{Reduction of Area}}$
" " "F" = Tensile Strength × Reduction of Area
" " "G" = Tensile Strength × Izod Impact Value
" " "H" = Elastic Limit × Izod Impact Value

Merit Values for Individual Service:

For some types of structural service, for example, the cables in suspension bridges, it is assumed that a steel having an elongation in 2 in. of 6 per cent is ductile enough. To evaluate the relative worth of a series of steels for such a service it would only be necessary to find the greatest strength with this minimum elongation, although it will, doubtless, be wise in the interest of safety to make a Charpy or Izod impact test for steels of *much* greater strength than had been

TABLE I.—QUALITY FACTOR "A."

Quality Factor "A" = Tensile Strength × Elongation in 2 in.

Rank	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Quality Factor "A"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	133 000	30.0	3 990 000	Cr, 0.92; V, 0.20; C, 0.26	Oil 1155	(1) p. 382
2	195 120	20.2	3 941 424	Cr, 12.5; C, 0.11	Oil 1000	(5) Table II, p. 802
3	191 370	19.5	3 731 715	Cr, 12.5; C, 0.11	Oil 900	(5) Table II, p. 802
4	192 870	17.5	3 375 225	Cr, 12.5; C, 0.11	Oil 500	(5) Table II, p. 802
5	167 000	20.0	3 340 000	Cr, 0.95; V, 0.18; C, 0.45	Oil	(4) Table VIII, p. 873
6	242 000	13.5	3 267 000	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
7	186 250	17.5	3 259 000	Cr, 12.5; C, 0.11	Oil 700	(5) Table II, p. 802
8	112 300	28.8	3 234 240	Cr, 10.89; Ni, 34.7; C, 0.39	As received	(3) Table V, p. 6
9	168 420	19.0	3 199 980	Cr, 0.51; C, 0.47	Water 1000	(1) p. 336
10	168 100	19.0	3 193 900	Cr, 16.00; C, 0.09	Water 900	(6) Table I, p. 1478
11	179 000	17.5	3 132 500	Cr. 0.52; Ni, 1.64; C, 0.545	Water 1000	(1) Fig. 240, p. 357
12	106 000	29.3	3 105 800	Ni, 4.5 to 5.25; C, 0.17	Oil 1200	(8) p. 7
13	155 000	20.0	3 100 000	Cr, 12.5; C, 0.11	Oil 1100	(5) Table II, p. 802
14	137 500	22.5	3 093 750	Cr, 0.32; Ni, 3.11; C, 0.47	Oil 750	(3) Table V, p. 6
15	103 400	29.5	3 050 300	C, 1.09; Mn, 0.33	Annealed. 1475	(3) Table V, p. 6
16	275 000	11.0	3 025 000	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
17	155 000	19.5	3 022 500	Cr, 16.00; C, 0.09	Water 1000	(6) Table I, p. 1478
18	120 550	25.0	3 013 750	Cr, 0.51; C, 0.47	Water 1300	(1) p. 336
19	151 000	19.9	3 004 900	C, 0.40; Mayari[a]	Water 1000	(1) p. 376
20	166 500	18.0	2 997 000	Cr, 11.78; C, 0.08	Oil 900	(3) Table V, p. 6

[a] Low nickel, low chromium. Exact analysis not supplied.

TABLE II.—QUALITY FACTOR "B."

Quality Factor "B" = Elastic Limit × Reduction of Area.

Rank	Elastic Limit, lb. per sq. in.	Reduction of Area, per cent	Quality Factor "B"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	209 000	48.7	10 178 300	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 600	(1) Fig. 246, p. 368
2	187 000	53.8	10 060 600	Ni, 5.00; C, 0.33	Oil 600	(1) Fig. 220, p. 329
3	244 000	40.8	9 955 200	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 400	(1) Fig. 246, p. 368
4	192 000	51.6	9 907 200	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
5	204 000	48.5	9 894 000	Ni, 5.00; C, 0.43	Oil 600	(1) Fig. 221, p. 330
6	181 000	54.5	9 864 500	Ni, 3.35; C, 0.33	Water 600	(1) Fig. 214, p. 320
7	234 000	41.5	9 711 000	Ni, 3.5; C, 0.37	Oil 400	(1) Fig. 216, p. 322
8	235 000	41.2	9 682 000	Ni, 5.00; C, 0.33	Oil 400	(1) Fig. 220, p. 329
9	253 000	38.0	9 614 000	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
10	176 200	54.5	9 602 900	Cr, 0.92; V, 0.20; C, 0.26	Water 840	(1) p. 382
11	199 000	47.5	9 452 500	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 600	(8) p. 16
12	166 800	56.5	9 424 200	Cr, 0.92; V, 0.20; C, 0.26	Water 930	(1) p. 382
13	176 580	52.2	9 217 476	Ni, 3.41; V, 0.20; C, 0.29	Water 750	(1) p. 385
14	173 300	52.7	9 132 910	Ni, 3.41; V, 0.20; C, 0.29	Water 840	(1) p. 385
15	149 700	60.4	9 041 880	Cr, 0.92; V, 0.20; C, 0.26	Water 1110	(1) p. 382
16	171 500	52.5	9 003 750	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 800	(8) p. 6
17	156 000	57.5	8 970 000	Ni, 3.35; C, 0.33	Water 800	(1) Fig. 214, p. 320
18	210 000	42.5	8 925 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
19	165 000	53.6	8 844 000	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 800	(1) Fig. 246, p. 368
20	189 000	46.5	8 821 050	C, 0.47; Ni, 3.11; Si, 1.58	Oil 750	(3) Table V, p. 6

TABLE III.—QUALITY FACTOR "C."

Quality Factor "C" = Elastic Limit × Elongation in 2 in.

Rank	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Quality Factor "C"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	99 020	30.0	2 970 600	Cr, 0.92; V, 0.20; C, 0.26	Oil 750	(1) p. 382
2	153 720	19.0	2 920 680	Cr, 0.51; C, 0.47	Water 1000	(1) p. 336
3	146 000	19.9	2 905 400	C, 0.40; Mayari[a]	Water 1000	(1) Fig. 250, p. 376
4	253 000	11.0	2 783 000	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 1400	(8) p. 16
5	157 000	17.5	2 747 500	Cr, 0.52; Ni, 1.64; C, 0.545	Water 1000	(1) Fig. 240, p. 357
6	171 500	16.0	2 744 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 800	(8) p. 6
7	109 540	25.0	2 738 500	Cr, 0.51; C, 0.47	Water 1300	(1) p. 336
8	235 000	11.4	2 679 000	Ni, 5.00; C, 0.33	Oil 400	(1) Fig. 220, p. 329
9	130 000	20.5	2 665 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 1000	(8) p. 6
10	120 750	22.0	2 656 500	Cr, 0.51; C, 0.47	Water 1200	(1) p. 336
11	234 000	11.3	2 644 200	Ni, 3.50; C, 0.37	Oil 400	(1) Fig. 216, p. 322
12	170 000	15.5	2 635 000	Cr, 1.02; V, 0.20; C, 0.50	Oil 1110	(1) p. 383
13	210 000	12.5	2 625 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
14	244 000	10.7	2 610 000	Cr, 0.75; Ni, 3.00: C, 0.40	Oil 400	(1) Fig. 246, p. 368
15	230 000	11.3	2 599 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 400	(8) p. 6
16	192 000	13.5	2 592 000	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
17	135 900	19.0	2 582 100	Cr, 16.00; C, 0.09	Water 900	(6) Table I, p. 1478
18	177 250	14.5	2 570 125	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
19	205 000	12.5	2 562 500	Cr, 0.52; Ni, 1.64; C, 0.545	Water 800	(1) Fig. 240, p. 357
20	168 000	14.9	2 503 200	C, 0.40; Mayari[a]	Water 800	(1) Fig. 250, p. 376

[a] Low nickel, low chromium. Exact analysis not supplied.

TABLE IV.—QUALITY FACTOR "D"

Quality Factor "D" = Elastic Limit × Elongation in 2 in. × Reduction of Area.

Rank	Elastic-Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Quality Factor "D"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	99 020	30.0	69.9	207 644 940	Cr, 0.92; V, 0.20; C, 0.26	Oil 1155	(1) p. 382
2	109 540	25.0	67.6	185 122 600	Cr, 0.51; C, 0.47	Water 1300	(1) p. 336
3	120 750	22.0	60.5	160 718 250	Cr, 0.51; C, 0.47	Water 1200	(1) p. 336
4	78 000	29.3	70.0	159 978 000	Ni, 4.50 to 5.25; C, 0.17	Oil 1200	(8) p. 7
5	130 000	20.5	60.0	159 900 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 1000	(8) p. 6
6	146 000	19.9	54.3	157 763 220	C, 0.40; Mayari[a]	Water 1000	(1) Fig. 250, p. 376
7	107 000	23.0	64.1	157 750 100	Cr, 0.75; Ni, 3.50; C, 0.40	Oil 1200	(1) Fig. 246, p. 368
8	99 000	25.2	62.7	156 423 960	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 1200	(8) p. 6
9	102 000	23.8	63.9	155 123 640	C, 0.40; Mayari[a]	Water 1200	(1) Fig. 250, p. 376
10	153 720	19.0	52.6	153 627 768	Cr, 0.51; C, 0.47	Water 1000	(1) p. 336
11	93 000	23.9	68.8	152 921 760	Ni, 4.50 to 5.25; C, 0.17	Oil 1000	(8) p. 7
12	96 510	24.0	65.5	151 713 720	Cr, 16.0; C, 0.09	Water 1100	(6) Table 1, p. 1478
13	133 000	18.0	62.5	149 625 000	Cr, 0.92; V, 0.20; C, 0.26	Water 1155	(1) p. 382
14	128 860	19.0	60.2	147 390 068	Cr, 0.51; C, 0.47	Water 1100	(1) p. 336
15	109 000	22.0	61.4	147 237 200	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 1200	(8) p. 16
16	114 000	21.0	61.5	147 231 000	Cr, 2.00; C, 0.50	Water 1300	(1) p. 345
17	102 800	21.6	65.8	146 107 584	Ni, 3.47; C, 0.32	Water 1000	(3) Table 5, p. 6
18	149 700	16.0	60.4	144 670 080	Cr, 0.92; V, 0.20; C, 0.26	Water 1110	(1) p. 382
19	171 500	16.0	52.5	144 060 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 800	(8) p. 6
20	125 800	19.5	58.3	143 015 730	Cr, 16.0; C, 0.09	Water 1000	(6) Table 1, p. 1478

[a] Low nickel, low chromium. Exact analysis not supplied.

TABLE V.—QUALITY FACTOR "E."

$$\text{Quality Factor ``E''} = \text{Elastic Limit} \times \sqrt{\text{Elongation in 2 in.} \times \text{Reduction of Area.}}$$

Rank	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Quality Factor "E"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	253 000	11.0	38.0	5 161 200	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55...	Oil..... 400	(8) p. 16
2	235 000	11.4	41.2	5 076 000	Ni, 5.00; C, 0.33...........	Oil..... 400	(1) Fig. 220, p. 329
3	244 000	10.7	40.8	5 075 200	Cr, 0.75; Ni, 3.00; C, 0.40..	Oil..... 400	(1) Fig. 246, p. 368
4	234 000	11.3	41.5	5 054 400	Ni, 3.50; C, 0.37...........	Oil..... 400	(1) Fig. 216, p. 322
5	192 000	13.5	51.6	5 049 600	Ni, 3.35; C, 0.33...........	Water.. 400	(1) Fig. 214, p. 320
6	181 000	13.8	54.5	4 959 400	Ni, 3.35; C, 0.33...........	Water.. 600	(1) Fig. 214, p. 320
7	171 500	16.0	52.5	4 956 350	Ni, 3.25 to 3.75; C, 0.40 to 0.50....................	Oil..... 800	(8) p. 6
8	187 000	12.7	53.8	4 880 700	Ni, 5.00; C, 0.33...........	Oil..... 600	(1) Fig. 220, p. 329
9	209 000	11.2	48.7	4 869 700	Cr. 0.75; Ni, 3.00; C, 0.40..	Oil..... 600	(1) Fig. 246, p. 368
10	153 720	19.0	52.6	4 857 552	Cr, 0.51; C, 0.47...........	Water.. 1000	(1) p. 336
11	210 000	12.5	42.5	4 830 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50....................	Oil..... 600	(8) p. 6
12	146 000	19.9	54.3	4 788 800	C, 0.40; Mayari[a]..........	Water.. 1000	(1) Fig. 250, p. 376
13	204 000	11.1	48.5	4 732 800	Ni, 5.00; C, 0.43...........	Oil..... 600	(1) Fig. 221, p. 330
14	199 000	11.7	47.5	4 676 500	Cr, 0.6 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55.....	Oil..... 600	(8) p. 16
15	156 000	15.6	57.5	4 664 400	Ni, 3.35; C, 0.33...........	Water.. 800	(1) Fig. 214, p. 320
16	177 250	14.5	47.5	4 643 950	Cr, 1.02; V, 0.20; C, 0.50...	Oil..... 1020	(1) p. 383
17	149 700	16.0	60.4	4 640 700	Cr, 0.92; V, 0.20; C, 0.26...	Water.. 1110	(1) p. 382
18	157 000	17.5	49.4	4 615 800	Cr, 0.52; Ni, 1.64; C, 0.545.	Water.. 1000	(1) Fig. 240, p. 357
19	188 000	13.1	45.9	4 606 000	Ni, 3.50; C, 0.37...........	Oil..... 600	(1) Fig. 216, p. 322
20	176 200	12.5	54.5	4 598 820	Cr, 0.92; V, 0.20; C, 0.26...	Water.. 840	(1) p. 382

[a] Low nickel, low chromium. Exact analysis not supplied.

TABLE VI.—QUALITY FACTOR "F."

$$\text{Quality Factor ``F''} = \text{Tensile Strength} \times \text{Reduction of Area.}$$

Rank	Tensile Strength, lb. per sq. in.	Reduction of Area, per cent	Quality Factor "F"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	242 000	51.6	12 487 200	Ni, 3.35; C, 0.33..............	Water.. 400	(1) Fig. 214, p. 320
2	195 120	62.5	12 195 000	Cr, 12.5; C, 0.11..............	Oil..... 1000	(5) Table II, p. 802
3	191 370	62.2	11 903 214	Cr, 12.5; C, 0.11..............	Oil..... 900	(5) Table II, p. 802
4	186 250	62.4	11 622 000	Cr, 12.5; C, 0.11..............	Oil..... 700	(5) Table II, p. 802
5	213 000	54.5	11 608 500	Ni, 3.35; C, 0.33..............	Water.. 600	(1) Fig. 214, p. 320
6	192 870	60.0	11 572 200	Cr, 12.5; C, 0.11..............	Oil..... 500	(5) Table II, p. 802
7	234 000	48.7	11 395 800	Cr, 0.75; Ni, 3.00; C, 0.40.....	Oil..... 600	(1) Fig. 246, p. 368
8	204 800	54.5	11 161 600	Cr, 0.92; V, 0.20; C, 0.26......	Water.. 840	(1) p. 382
9	270 000	40.8	11 016 000	Cr, 0.75; Ni, 3.00; C, 0.40.....	Oil..... 400	(1) Fig. 246, p. 368
10	265 000	41.5	10 997 500	Ni, 3.50; C, 0.37..............	Oil..... 400	(1) Fig. 216, p. 322
11	224 000	47.5	10 640 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55..............	Oil..... 600	(8) p. 16
12	275 000	38.0	10 450 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55..............	Oil..... 400	(8) p. 16
13	214 000	48.5	10 379 000	Ni, 5.00; C, 0.43..............	Oil..... 600	(1) Fig. 221, p. 330
14	155 000	66.9	10 369 500	Cr, 12.5; C, 0.11..............	Oil..... 1100	(5) Table II, p. 802
15	183 200	56.5	10 350 800	Cr, 0.92; V, 0.20; C, 0.26......	Water.. 930	(1) p. 382
16	166 000	62.3	10 341 800	Ni, 4.5 to 5.25; C, 0.12........	Oil..... 600	(8) p. 7
17	188 000	55.0	10 340 000	Cr, 0.80; Ni, 3.00; C, 0.35.....	Oil..unknown	(4) Table VIII, p. 873
18	178 000	57.5	10 235 000	Ni, 3.35; C, 0.33..............	Water.. 800	(1) Fig. 214, p. 320
19	195 200	52.2	10 189 440	Ni, 3.41; V, 0.20; C, 0.29......	Water.. 750	(1) p. 385
20	184 000	54.9	10 101 600	Ni, 4.5 to 5.25; C, 0.12........	Oil..... 400	(8) p. 7

TABLE VII.—QUALITY FACTOR "G."

Quality Factor "G" = Tensile Strength × Izod Value.

Rank	Tensile Strength, lb. per sq. in.	Izod Value, ft-lb.	Quality Factor "G"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	192 870	60	11 572 200	Cr, 12.5; C, 0.11	Oil...... 500	(5) Table II, p. 802
2	97 500	116.5	11 358 750	Cr, 12.5; C, 0.11	Oil...... 1400	(5) Table II, p. 802
3	186 250	60	11 175 000	Cr, 12.5; C, 0.11	Oil...... 700	(5) Table II, p. 802
4	118 620	92.5	10 972 350	Cr, 12.5; C, 0.11	Oil...... 1200	(5) Table II, p. 802
5	103 370	102	10 543 740	Cr, 12.5; C, 0.11	Oil...... 1300	(5) Table II, p. 802
6	102 600	98.5	10 106 100	Cr, 16.0; C, 0.09	Water... 1400	(6) Table I, p. 1478
7	100 600	96.0	9 657 600	Cr, 16.0; C, 0.09	Water... 1300	(6) Table I, p. 1478
8	191 370	49.5	9 472 815	Cr, 12.5; C, 0.11	Oil...... 900	(5) Table II, p. 802
9	144 100	62.5	9 006 250	Mn, 1.17; Si, 0.31; C, 0.51	Unknown 900	(2) Table III, p. 5
10	142 800	62.6	8 939 280	Mn, 1.17; Si, 0.31; C, 0.51	Unknown 900	(2) Table III, p. 5
11	112 500	76.5	8 606 250	Mn, 0.67; Si, 0.20; C, 0.41	Unknown 900	(2) Table III, p. 5
12	107 900	77.1	8 319 090	Mn, 0.67; Si, 0.20; C, 0.41	Unknown 900	(2) Table III, p. 5
13	108 000	70.0	7 560 000	Cr, 16.0; C, 0.09	Water... 1200	(6) Table I, p. 1478
14	89 660	84.0	7 531 440	Cr, 16.0; C, 0.09	Water... 1500	(6) Table I, p. 1478
15	144 100	51.5	7 421 150	Mn, 1.75; Si, 0.10; C, 0.38	Unknown 900	(2) Table III, p. 5
16	169 000	42	7 098 000	Mn, 0.97; Si, 0.90; C, 0.28	Water... 800	(4) Table VII, p. 873
17	142 100	48.1	6 835 010	Ni, 4.67; C, 0.23	Unknown 900	(2) Table III, p. 5
18	115 000	59	6 785 000	Mn, 0.97; Si, 0.90; C, 0.28	Oil...... 800	(4) Table VII, p. 873
19	141 500	45.6	6 452 400	Ni, 4.61; C, 0.23	Unknown 900	(2) Table III, p. 5
20	195 120	33.0	6 438 960	Cr, 12.5; C, 0.11	Oil...... 1000	(5) Table II, p. 802

TABLE VIII.—QUALITY FACTOR "H."

Quality Factor "H" = Elastic Limit × Izod Value.

Rank	Elastic Limit, lb. per sq. in.	Izod Value, ft-lb.	Quality Factor "H"	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
1	78 300	96	7 516 800	Cr, 16.0; C, 0.09	Water... 1300	(6) Table I, p. 1478
2	78 000	92.5	7 215 000	Cr, 12.5; C, 0.11	Oil...... 1200	(5) Table II, p. 802
3	71 760	98.5	7 068 360	Cr, 16.0; C, 0.09	Water... 1400	(6) Table I, p. 1478
4	60 000	116.5	6 990 000	Cr, 12.5; C, 0.11	Oil...... 1400	(5) Table II, p. 802
5	109 500[a]	62.6	6 854 700	Mn, 1.17; Si, 0.31; C, 0.51	Unknown 900	(2) Table III, p. 5
6	114 000	60	6 840 000	Cr, 12.5; C, 0.11	Oil...... 700	(5) Table II, p. 802
7	63 000	102	6 426 000	Cr, 12.5; C, 0.11	Oil...... 1300	(5) Table II, p. 802
8	101 900[a]	62.5	6 368 750	Mn, 1.17; Si, 0.31; C, 0.51	Unknown 900	(2) Table III, p. 5
9	127 600[a]	48.1	6 137 560	Ni, 4.61; C, 0.23	Unknown 900	(2) Table III, p. 5
10	76 400[a]	76.5	5 844 600	Mn, 0.67; Si, 0.20; C, 0.41	Unknown 900	(2) Table III, p. 5
11	82 520	70	5 776 400	Cr. 16.0; C, 0.09	Water... 1200	(6) Table I, p. 1478
12	112 000[a]	51.5	5 768 000	Mn, 1.75; Si, 0.10; C, 0.38	Unknown 900	(2) Table III, p. 5
13	94 000	60	5 640 000	Cr, 12.5; C, 0.11	Oil...... 500	(5) Table II, p. 802
14	123 500[a]	45.6	5 635 600	Ni, 4.61; C, 0.23	Unknown 900	(2) Table III, p. 5
15	112 500	49.5	5 568 750	Cr, 12.5; C, 0.11	Oil...... 900	(5) Table II, p. 802
16	71 500[a]	77.1	5 512 650	Mn, 0.67; Si, 0.20; C, 0.41	Unknown 900	(2) Table III, p. 5
17	145 200[a]	34.5	5 009 400	Cr, 1.32; Ni, 3.03; C, 0.42	Unknown 900	(2) Table III, p. 5
18	59 100	84	4 964 400	Cr, 16.0; C, 0.09	Water... 1500	(6) Table I, p. 1478
19	130 400[a]	37.8	4 929 120	Ni, 3.61; C, 0.27	Unknown 900	(2) Table III, p. 5
20	142 600[a]	32.9	4 691 540	Cr, 1.32; Ni, 3.03; C, 0.42	Unknown 900	(2) Table III, p. 5

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[a] Proportional limit—no elastic limit given. Specimens were quenched but the quenching medium is not given.

TABLE IX.—RELATIVE ELONGATION FOR SPECIFIED TENSILE STRENGTH.

Rank	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
TENSILE STRENGTH = 150,000 TO 175,000 LB. PER SQ. IN.					
1	167 000	20.0	Cr, 0.95; V, 0.18; C, 0.45	Oil	(4) Table VIII, p. 873
2	155 000	20.0	Cr, 12.5; C, 0.11	Oil 1100	(5) Table II, p. 802
3	151 000	19.9	C, 0.40; Mayari^a	Water 1000	(1) Fig. 250, p. 376
4	155 000	19.5	Cr, 16.00; C, 0.09	Water 1000	(6) Table I, p. 1478
5	168 400	19.0	Cr, 0.51; C, 0.47	Water 1000	(1) p. 336
6	168 100	19.0	Cr, 16.00; C, 0.09	Water 900	(6) Table I, p. 1478
7	156 000	18.0	Cr, 0.92; V, 0.20; C, 0.26	Water 1155	(1) p. 382
8	151 000	18.0	Cr, 0.38; Mn, 1.04; Si, 0.91; C, 0.34	Oil 930	(4) Table VIII, p. 873
9	149 700	17.9	Ni, 3.61; C, 0.27	Quenched 900	(2) Table III, p. 5
10	150 000	17.5	Ni, 3.41; V, 0.20; C, 0.29	Oil 1110	(1) p. 385
TENSILE STRENGTH = 175,000 TO 200,000 LB. PER SQ. IN.					
1	195 120	20.2	Cr, 12.5; C, 0.11	Oil 1000	(5) Table II, p. 802
2	191 370	19.5	Cr, 12.5; C, 0.11	Oil 900	(5) Table II, p. 802
3	192 870	17.5	Cr, 12.5; C, 0.11	Oil 500	(5) Table II, p. 802
4	186 250	17.5	Cr, 12.5; C, 0.11	Oil 700	(5) Table II, p. 802
5	179 000	17.5	Cr, 0.52; Ni, 1.64; C, 0.545	Water 1000	(1) Fig. 240, p. 357
6	178 000	15.6	Ni, 3.35; C, 0.33	Water 800	(1) Fig. 214, p. 320
7	186 800	15.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 1110	(1) p. 383
8	178 000	15.0	Cr, 1.10; Ni, 1.75; C, 0.30	Oil	(4) Table VIII, p. 873
9	192 000	14.9	C, 0.40; Mayari^a	Water 800	(1) Fig. 250, p. 376
10	190 000	14.9	Ni, 4.5 to 5.25; C, 0.17	Oil 300	(8) p. 7
TENSILE STRENGTH = 200,000 TO 225,000 LB. PER SQ. IN.					
1	200 000	14.0	Cr, 1.00; V, 0.18; C, 0.30	Water	(4) Table VIII, p. 873
2	213 000	13.8	Ni, 3.35; C, 0.33	Water 600	(1) Fig. 214, p. 320
3	200 000	13.1	Ni, 3.50; C, 0.37	Oil 600	(1) Fig. 216, p. 322
4	201 150	13.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
5	204 000	12.7	Ni, 5.00; C, 0.33	Oil 600	(1) Fig. 220, p. 329
6	209 400^b	12.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
7	204 800	12.5	Cr, 0.92; V, 0.20; C, 0.26	Water 840	(1) p. 382
8	215 400^c	12.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
9	224 000	11.7	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 600	(8) p. 16
10	214 000	11.1	Ni, 5.0; C, 0.43	Oil 600	(1) Fig. 221, p. 330
TENSILE STRENGTH = 225,000 TO 250,000 LB. PER SQ. IN.					
1	242 000	13.5	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
2	233 000	12.5	Cr, 0.52; Ni, 1.64; C, 0.546	Water 800	(1) Fig. 240, p. 357
3	231 000	12.5	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
4	242 000	11.4	Ni, 5.00; C, 0.33	Oil 400	(1) Fig. 220, p. 329
5	234 000	11.2	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 600	(1) Fig. 246, p. 368
6	237 750^c	10.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 840	(1) p. 383
7	227 000^b	10.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 840	(1) p. 383
8	227 000	9.5	C, 0.40; Mayari^a	Water 600	(1) Fig. 250, p. 376
9	228 200	9.0	Cr, 2.00; C, 0.50	Water 750	(1) p. 345
10	226 000	8.2	Cr, 0.42; Ni, 1.35; C, 0.37	Oil 600	(1) Fig. 239, p. 356
TENSILE STRENGTH = 250,000 TO 300,000 LB. PER SQ. IN.					
1	265 000	11.3	Ni, 3.5; C, 0.37	Oil 400	(1) Fig. 216, p. 322
2	260 000	11.3	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 400	(8) p. 6
3	275 000	11.0	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
4	270 000	10.7	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 400	(1) Fig. 246, p. 368
5	270 000	8.7	Cr, 0.52; Ni, 1.64; C, 0.545	Water 600	(1) Fig. 240, p. 357
6	260 500^c	8.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
7	264 000^b	6.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
8	292 000	6.3	Cr, 0.52; Ni, 1.64; C, 0.545	Water 400	(1) Fig. 240, p. 357

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[a] Low nickel, low chromium. Exact analysis not supplied.

[b] Quenched from 1650° F.

[c] Quenched from 1520° F.

TABLE X.—RELATIVE ELONGATION FOR SPECIFIED ELASTIC LIMIT.

Rank	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
ELASTIC LIMIT = 100,000 TO 125,000 LB. PER SQ. IN.					
1	99 000	30.0	Cr, 0.92; V, 0.20; C, 0.26	Oil 1155	(1) p. 382
2	99 000	25.2	Ni, 3.25 to 3.75; C, 0.45 to 0.55	Oil 1200	(8) p. 6
3	109 500	25.0	Cr. 0.51; C, 0.47	Water 1300	(1) p. 336
4	102 000	23.9	Ni, 5.00; C, 0.33	Oil 1200	(1) Fig. 220, p. 329
5	102 000	23.8	C, 0.40; Mayari[a]	Water 1200	(1) Fig. 250, p. 376
6	101 000	22.5	Cr, 0.52; Ni, 1.64; C, 0.545	Water 1200	(1) Fig. 240, p. 357
7	109 000	22.0	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 1200	(8) p. 16
8	114 000	21.0	Cr, 2.00; C, 0.50	Water 1300	(1) p. 345
9	115 000	20.0	Cr, 2.00; C, 0.85	Water 1300	(1) p. 345
10	112 000	20.0	Cr, 0.92; V, 0.20; C, 0.26	Oil 1110	(1) p. 382
ELASTIC LIMIT = 125,000 TO 150,000 LB. PER SQ. IN.					
1	130 000	20.5	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 1000	(8) p. 6
2	146 000	19.9	C, 0.40; Mayari[a]	Water 1000	(1) Fig. 250, p. 376
3	125 800	19.5	Cr, 16.0; C, 0.09	Water 1000	(6) Table I, p. 1478
4	135 900	19.0	Cr, 16.0; C, 0.09	Water 900	(6) Table I, p. 1478
5	128 900	19.0	Cr, 0.51; C, 0.47	Water 1100	(1) p. 336
6	126 000	18.8	Ni, 3.35; C, 0 33	Water 1000	(1) Fig. 214, p. 320
7	126 000	18.5	Ni, 3.41; V, 0.20; C, 0.29	Water 1160	(1) p. 385
8	127 600	18.3	Ni, 4.61; C, 0.23	Unknown 900	(2) Table III, p. 5
9	133 000	18.0	Cr, 0.92; V, 0.20; C, 0.26	Water 1155	(1) p. 382
10	130 400	17.9	Ni, 3.61; C, 0.27	Unknown 900	(2) Table III, p. 5
ELASTIC LIMIT = 150,000 TO 175,000 LB. PER SQ. IN.					
1	153 720	19	Cr, 0.51; C, 0.47	Water 1000	(1) p. 336
2	157 000	17.5	Cr, 0.52; Ni, 1.64; C, 0.545	Water 1000	(1) Fig. 240, p. 357
3	171 500	16.0	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 800	(8) p. 6
4	149 700	16.0	Cr, 0.92; V, 0.20; C, 0.26	Water 1110	(1) p. 382
5	156 000	15.6	Ni, 3.35; C, 0.33	Water 800	(1) Fig. 214, p. 320
6	170 000	15.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 1110	(1) p. 383
7	161 000	15.1	Ni, 5.00; C, 0.42	Oil 800	(1) Fig. 221, p. 330
8	151 800	15.0	Cr, 2.00; C, 0.32	Water 1025	(1) p. 345
9	168 000	14.9	C, 0.40; Mayari[a]	Water 800	(1) Fig. 250, p. 376
10	154 000	14.9	Ni, 4.5 to 5.25; C, 0.17	Oil 300	(8) p. 7
ELASTIC LIMIT = 175,000 TO 200,000 LB. PER SQ. IN.					
1	177 250[b]	14.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
2	181 000	13.8	Ni, 3.35; C, 0.33	Water 600	(1) Fig. 214, p. 320
3	192 000	13.5	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
4	188 000	13.1	Ni, 3.50; C, 0.37	Oil 600	(1) Fig. 216, p. 322
5	186 000[c]	13.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
6	187 000	12.7	Ni, 5.0; C, 0.33	Oil 600	(1) Fig. 220, p. 32
7	176 200	12.5	Cr, 0.92; V, 0.20; C, 0.26	Water 840	(1) p. 382
8	193 000[b]	12.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 920	(1) p. 383
9	176 580	12.0	Ni, 3.41; V, 0.20; C, 0.29	Water 750	(1) p. 385
10	199 000	11.7	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 600	(8) p. 16
ELASTIC LIMIT = 200,000 TO 225,000 LB. PER SQ. IN.					
1	210 000	12.5	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
2	205 000	12.5	Cr, 0.52; Ni, 1.46; C, 0.545	Water 800	(1) Fig. 240, p. 357
3	209 000	11.2	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 600	(1) Fig. 246, p. 368
4	204 000	11.1	Ni, 5.00; C, 0.43	Oil 600	(1) Fig. 221, p. 330
5	217 400[c]	10.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 840	(1) p. 383
6	213 400[b]	10.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 840	(1) p. 383
7	224 000	9.0	Cr, 2.00; C, 0.50	Water 750	(1) p. 345
8	216 000	8.2	Cr, 0.42; Ni, 1.35; C, 0.26	Oil 600	(1) Fig. 239, p. 356
ELASTIC LIMIT = 225,000 TO 275,000 LB. PER SQ. IN.					
1	235 000	11.4	Ni, 5.0; C, 0.33	Oil 400	(1) Fig. 220, p. 329
2	234 000	11.3	Ni, 3.55; C, 0.37	Oil 400	(1) Fig. 216, p. 322
3	230 000	11.3	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 400	(8) p. 6
4	253 000	11.0	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
5	244 000	10.7	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 400	(1) Fig. 246, p. 368
6	245 000	8.7	Cr, 0.52; Ni, 1.64; C, 0.545	Water 600	(1) Fig. 240, p. 357
7	240 000[b]	8.0	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
8	239 700[c]	6.5	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
9	270 000	6.3	Cr, 0.52; Ni, 1.64; C, 0.545	Water 400	(1) Fig. 240, p. 357
10	239 000	6.3	Cr, 0.42; Ni, 1.35; C, 0.37	Oil 400	(1) Fig. 239 ,p. 356

[a] Low nickel, low chromium. **Exact analysis not applied.**

[b] Quenched from 1520° F.

[c] Quenched from 1650° F.

used over a period of years with safety in the same service. For other types of structural work, it is considered that an elongation in 2 in. of 12 per cent is indication of sufficient ductility; and for still other types of service the minimum elongation must be 20 per cent.

Again it may be necessary to have a very high tensile strength, or else a high elastic limit, as the minimum requirement for some types of service where strength is imperative and either space or weight is limited. In this case it is necessary to assign a minimum tensile strength or a minimum elastic limit and then choose the steel having the highest ductility.

TABLE XI.—RELATIVE TENSILE STRENGTH FOR SPECIFIED ELONGATION IN 2 IN.

Rank	Elongation in 2 in., per cent	Tensile Strength, lb. per sq. in.	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
			ELONGATION IN 2 IN. = 6 TO 11 PER CENT (INCLUSIVE).		
1	6.3	292 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 400	(1) Fig. 240, p. 357
2	11.0	275 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
3	10.7	270 000	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 400	(1) Fig. 246, p. 368
4	8.7	270 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 600	(1) Fig. 240, p. 357
5	11.3	265 000	Ni, 3.5; C, 0.37	Oil 400	(1) Fig. 216, p. 322
6	6.5	264 500	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
7	8.0	260 500	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
8	11.3	260 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 400	(8) p. 6
9	6.3	248 000	Cr, 0.42; Ni, 1.35; C, 0.37	Oil 400	(1) Fig. 239, p. 356
10	11.4	242 000	Ni, 5.00; C, 0.33	Oil 400	(1) Fig. 220, p. 329
			ELONGATION IN 2 IN. = 12 TO 19 PER CENT (INCLUSIVE)		
1	13.5	242 000	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
2	12.5	233 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 800	(1) Fig. 240, p. 357
3	12.5	231 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
4	12.0	215 450	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
5	13.8	213 000	Ni, 3.35; C, 0.33	Water 600	(1) Fig. 214, p. 320
6	12.5	209 800	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
7	12.5	204 800	Cr, 0.92; V, 0.20; C, 0.26	Water 840	(1) p. 382
8	12.7	204 000	Ni, 5.00; C, 0.33	Oil 600	(1) Fig. 220, p. 329
9	13.0	201 150	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
10	14.0	200 000	Cr, 1.00; V, 0.18; C, 0.30	Water unknown	(4) Table VIII, p. 873
			ELONGATION IN 2 IN. = 20 PER CENT MINIMUM		
1	20.2	195 120	Cr, 12.5; C, 0.11	Oil 1000	(5) Table II, p. 802
2	20.0	167 000	Cr, 0.95; V, 0.18; C, 0.30	Oil unknown	(4) Table VIII, p. 873
3	20.0	155 000	Cr, 12.5; C, 0.11	Oil 1100	(5) Table II, p. 802
4	20.5	142 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 1000	(8) p. 6
5	20.0	137 000	Cr, 0.92; V, 0.20; C, 0.26	Oil 1110	(1) p. 382
6	30.0	133 000	Cr, 0.92; V, 0.20; C, 0.26	Oil 1155	(1) p. 382
	22.0	130 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 1200	(8) p. 16
8	20.0	126 000	Cr, 2.0; C, 0.85	Water 1300	(1) p. 345
9	22.5	125 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 1200	(1) Fig. 240, p. 357
10	21.0	124 800	Cr, 2.00; C, 0.85	Water 1300	(1) p. 345

SELECTION OF PHYSICAL TEST DATA

The task of selecting the physical test data which would form the nucleus of a paper of this type was not an easy one. It was necessary that a broad field of alloy steels be combed and that the study also be expanded to include the various heat treatments which would assure the best physical properties of the chosen alloy steels. The material which was selected is given in the list of References appended hereto and represents what the authors would like to be a truly representative and entirely unbiased collection of alloy steel data. These publications were chosen, not entirely at random, but without regard to any preformed ideas or hypotheses, and for the purpose of getting as complete data as possible on chemical analysis and mechanical properties, including strength, ductility, and impact test. We are not at all certain that we have chosen the best material available, but at least it is the best which we have found and probably is as nearly representative as we could get. It would obviously be impossible to search the literature and take all the material found, because the calculations would be practically endless. (The figures contained

TABLE XII.—RELATIVE ELASTIC LIMIT FOR SPECIFIED ELONGATION IN 2 IN.

Rank	Elongation in 2 in., per cent	Elastic Limit, lb. per sq. in.	Chemical Analysis, per cent	Quench and Draw, deg. Fahr.	Reference
ELONGATION IN 2 IN. = 6 TO 11 PER CENT (INCLUSIVE)					
1	6.3	270 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 400	(1) Fig. 240, p. 357
2	11.0	253 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 400	(8) p. 16
3	8.7	245 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 600	(1) Fig. 240, p. 357
4	10.7	244 000	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 400	(1) Fig. 246, p. 368
5	8.0	240 000[a]	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
6	6.5	239 700[b]	Cr, 1.02; V, 0.20; C, 0.50	Oil 750	(1) p. 383
7	6.3	239 000	Cr, 0.42; Ni, 1.35; C, 0.37	Oil 400	(1) Fig. 239, p. 356
8	11.4	235 000	Ni, 5.00; C, 0.33	Oil 400	(1) Fig. 220, p. 329
9	11.3	234 000	Ni, 3.5; C, 0.37	Oil 400	(1) Fig. 216, p. 320
10	11.3	230 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 400	(8) p. 6
ELONGATION IN 2 IN. = 12 TO 19 PER CENT (INCLUSIVE)					
1	12.5	210 000	Ni, 3.25 to 3.75; C, 0.40 to 0.50	Oil 600	(8) p. 6
2	12.5	205 000	Cr, 0.52; Ni, 1.64; C, 0.545	Water 800	(1) Fig. 240, p. 357
3	12.0	193 100[a]	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
4	12.5	192 200[b]	Cr, 1.02; V, 0.20; C, 0.50	Oil 930	(1) p. 383
5	13.5	192 000	Ni, 3.35; C, 0.33	Water 400	(1) Fig. 214, p. 320
6	13.1	188 000	Ni, 3.5; C, 0.37	Oil 600	(1) Fig. 216, p. 322
7	12.7	187 000	Ni, 5.0; C, 0.33	Oil 600	(1) Fig. 220, p. 329
8	13.0	186 100	Cr, 1.02; V, 0.20; C, 0.50	Oil 1020	(1) p. 383
9	13.8	181 000	Ni, 3.35; C, 0.33	Water 600	(1) Fig. 214, p. 320
10	12.0	176 580	Ni, 3.41; V, 0.20; C, 0.29	Water 750	(1) p. 385
ELONGATION IN 2 IN. = 20 PER CENT MINIMUM					
1	20.5	130 000	Ni, 3.25 to 3.75; C, 0.40 to 0.55	Oil 1000	(8) p. 6
2	22.0	120 750	Cr, 0.51; C, 0.47	Water 1200	(1) p. 336
3	20.0	115 000	Cr, 2.00; C, 0.85	Water 1300	(1) p. 345
4	21.0	114 000	Cr, 2.00; C, 0.50	Water 1300	(1) p. 345
5	20.0	112 000	Cr, 0.92; V, 0.20; C, 0.26	Oil 1110	(1) p. 382
6	25.0	109 540	Cr, 0.51; C, 0.47	Water 1300	(1) p. 336
7	22.0	109 000	Cr, 0.60 to 0.95; Ni, 2.75 to 3.25; C, 0.45 to 0.55	Oil 1200	(8) p. 16
8	23.0	107 000	Cr, 0.75; Ni, 3.00; C, 0.40	Oil 1200	(1) Fig. 246, p. 368
9	22.6	106 000	Ni, 5.00; C, 0.43	Oil 1200	(1) Fig. 221, p. 330
10	23.9	102 000	Ni, 5.00; C, 0.33	Oil 1200	(1) Fig. 220, p. 329

[a] Quenched from 1520° F.
[b] Quenched from 1650° F.

TABLE XIII.—SUMMATION OF TABLES I TO XII.

	Quality Factor A Tensile Strength × Elongation	Quality Factor B Elastic Limit × Reduction of Area	Quality Factor C Elastic Limit × Elongation	Quality Factor D Elastic Limit × Elongation × Reduction of Area	Quality Factor E Elastic Limit × √Elongation × Reduction of Area	Quality Factor F Tensile Strength × Reduction of Area	Quality Factor G Tensile Strength × Izod	Quality Factor H Elastic Limit × Izod	Relative Elongations for Specified Tensile Strength					Relative Elongations for Specified Elastic Limit						Relative Tensile Strength for Specified Elongation			Relative Elastic Limit for Specified Elongation			Total Points
									150 000 to 175 000 lb. per sq. in.	175 000 to 200 000 lb. per sq. in.	200 000 to 225 000 lb. per sq. in.	225 000 to 250 000 lb. per sq. in.	250 000 to 300 000 lb. per sq. in.	100 000 to 125 000 lb. per sq. in.	125 000 to 150 000 lb. per sq. in.	150 000 to 175 000 lb. per sq. in.	175 000 to 200 000 lb. per sq. in.	200 000 to 225 000 lb. per sq. in.	225 000 to 250 000 lb. per sq. in.	6 per cent	12 per cent	20 per cent	6 per cent	12 per cent	20 per cent	
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	
Rank 1	6A	3A	6A	6A	3D	2B	5B	5C	6B	5B	6D	2B	2D	6A	2E	5A	6C	2E	2A	3C	2B	5B	3C	2E	2E	..
Rank 2	5B	2A	5A	5A	2A	5B	5B	5B	5B	5B	2B	3C	2E	2E	3B	5C	2B	3C	2D	3D	3C	6E	3D	3C	5A	..
Rank 3	5B	3A	3B	5A	3A	5B	5B	5C	3B	5B	2D	2E	3D	5A	3C	2E	2B	3A	2E	3A	2E	5B	3C	6C	5E	..
Rank 4	5B	2B	3A	2F	2D	5B	5B	5B	5C	5B	6C	2A	3A	2A	3C	6A	2D	2C	3D	3C	6C	2E	3A	6C	5D	..
Rank 5	6B	2C	3C	2E	2B	2B	5B	1A	5A	3C	2A	3A	3C	3B	5A	2B	6C	6C	3A	2E	2B	6A	6C	2B	6A	..
Rank 6	2B	2B	2E	3B	2B	5B	5C	5B	5C	2B	6C	6C	6C	3C	2B	6C	2A	6C	3C	6C	6C	6A	6C	2D	5A	..
Rank 7	5B	2D	5A	3A	2E	3A	5C	5B	6A	6C	6A	6C	6C	3D	2H	2C	6A	5D	6C	6C	6A	3D	3G	2A	3D	..
Rank 8	3E	2A	2A	2E	2A	5A	5B	1A	9A	3F	6C	3B	3C	5D	2 I	5F	6C	3G	6C	2E	2A	5E	2A	6C	3A	..
Rank 9	5A	3A	2E	3B	3B	3A	1A	2 I	2G	3B	3C	5D	..	5E	6A	3B	2H	..	3C	3G	6C	3C	2D	2B	2C	..
Rank 10	5C	6A	5A	5A	5A	3A	1A	1B	2H	2F	2C	3G	..	6A	2G	2F	3D	..	3G	2A	6D	5E	2E	2H	2A	..
RECAPITULATION [a]																										
No. 1. Manganese Steel	..	..	..	..	..	..	3	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	3
No. 2. Nickel Steel	5	34	10	16	34	16	..	2	3	6	24	25	19	16	23	19	31	17	27	10	27	7	6	28	13	416
No. 3. Chromium-Nickel Steel	3	20	21	11	20	7	..	..	8	11	2	19	24	15	24	2	1	20	21	36	9	6	38	9	7	334
No. 5. Chromium Steel	31	..	14	18	1	32	52	43	27	34	..	2	..	13	6	22	..	4	..	..	..	22	..	..	29	254
No. 6. Chromium-Vanadium Steel	16	1	10	10	..	..	..	..	14	..	29	9	9	11	2	12	23	11	7	9	19	20	11	18	6	247
No. 9. Silicon-Manganese Steel	..	..	..	..	..	..	..	..	3	4	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	7

[a] Steels classified as follows: Rank 1 = 10 points, Rank 2 = 9 points,........ Rank 10 = 1 point.

KEY (Chemical compositions in per cent):	A	B	C	D	E	F	G	H	I
No. 1. Manganese Steel	Mn, 1.17, Si, 0.31, C, 0.51	Mn, 0.67, Si, 0.20, C, 0.41	......	......	......	......	......	......	......
No. 2. Nickel Steel	Ni, 5.00, C, 0.33	Ni, 3.35, C, 0.33	Ni, 5.00, C, 0.43	Ni, 3.5, C, 0.37	Ni, 3.25 to 3.75, C, 0.40 to 0.50	Ni, 4.5 to 5.25, C, 0.17	Ni, 3.61, C, 0.27	Ni, 3.41, V, 0.20, C, 0.29	Ni, 4.61, C, 0.23
No. 3. Chromium-Nickel Steel	Cr, 0.75, Ni, 3.00, C, 0.40	C, 0.40, Mayari[a]	Cr, 0.52, Ni, 1.64, C, 0.545	Cr, 0.6 to 0.95, Ni, 2.75 to 3.25, C, 0.45 to 0.55	Cr, 10.89, Ni, 34.7, C, 0.39	Cr, 1.10, Ni, 1.75, C, 0.30	Cr, 0.42, Ni, 1.35, C, 0.37	......	......
No. 5. Chromium Steel	Cr, 0.51, C, 0.47	Cr, 12.5, C, 0.11	Cr, 16.0, C, 0.09	Cr, 2.00, C, 0.50	Cr, 2.00, C, 0.85	Cr, 2.00, C, 0.32	......	......	......
No. 6. Chromium-Vanadium Steel	Cr, 0.92, V, 0.20, C, 0.26	Cr, 0.95, V, 0.18, C, 0.45	Cr, 1.02, V, 0.20, C, 0.50	Cr, 1.00, V, 0.20, C, 0.30	Cr, 0.95, V, 18, C, 0.30	......	......	......	......
No. 9. Silicon-Manganese Steel	Cr, 0.38, Mn, 1.04, Si, 0.91, C, 0.34	......	......	......	......	......	......	......	......

[a] Low nickel, low chromium, exact analysis not supplied.

in Tables I to XIII, inclusive, occupied one man continuously copying and calculating for six weeks, besides the study and calculations which the two authors were able to give it.) Included in the study are low-manganese, nickel, nickel-chromium, chromium-molybdenum, chromium, chromium-vanadium and silico-manganese steels. There have been studied about fifty alloy steels of varying compositions and from these fifty or so steels, thirty have proved their worth in merit factors and have been given places of high rank in the final summation of merit factors. About 225 heat treatments of the combined selected steels have been culled to determine the best physical properties. The complete study of this number of heat treatments resulted in about 1800 calculations. These constituted but a small portion of the time consumed in the preparation of this paper, however, since the calculations merely provided food for thought. It is this "food for thought" that the authors are presenting the Society and it is hoped that it will instigate many and more conclusive studies in the same field.

DESCRIPTION OF TABLES

It is impossible, due to lack of space, to publish the original sources of data used in this paper, and for the reader's convenience throughout all of the tables the reference which supplies the initial physical properties for each mentioned steel is given.

Tables I to VIII, inclusive, embody a report upon the eight quality factors mentioned earlier. It was only possible to publish the highest twenty in ranking due to lack of space, but this number affords a fair study of the alloy steel fields.

Tables IX to XII, inclusive, are a résumé of merit values for individual service as explained earlier. Table IX represents a series of data which have been condensed to the ten alloy steels having the highest elongation for a specified tensile strength. The specified tensile strengths have been divided into five groups starting with 150,000 lb. per sq. in. and increasing in increments of 25,000 lb. per sq. in.

Table X provides a similar résumé of the alloy steels having the highest elongation but with a specified elastic limit. The elastic limits are in six groups, starting with 100,000 lb. per sq. in. and increasing in increments of 25,000 lb. per sq. in.

Table XI represents the ten alloy steels having the highest tensile strength for a specified elongation. The highest tensile strengths were chosen for minimum elongation values of 6 per cent, 12 per cent and 20 per cent.

Table XII represents a similar set of data, with the highest elastic limits being chosen for the same minimum elongation.

In order to evaluate the types of alloy steels for their respective worths both in quality factors and individual merit values, Table XIII was devised. In this table, the alloy steels are given their respective S.A.E. rating number and are followed by a letter to designate a particular chemical composition. In Table XIII, the highest ranking ten steels in each table have been chosen and listed. In the recapitulation of Table XIII, a value of ten points has been given to the steel ranking first in each respective table, nine points to second place, etc., and finally one point to tenth place. By glancing at a column in the recapitulation of Table XIII, the value of each type of alloy steel for that particular combination of physical data is obtained. By the addition of points in the rows following each type of steel an integration of the value of an alloy steel for the entire series of quality factors and merit values is obtained.

It will be noticed that the same composition steel appears more than one time in one column in Table XIII. This indicates that one alloy steel may have several heat treatments each of which will give that steel a higher rank for a certain quality or merit factor than some other alloy steel.

DISCUSSION OF RESULTS

It will be evident from a study of Tables I to XIII that there are some steels much used in structural work, not because of their superiority in mechanical properties, but on account of some such reason as ease of fabrication, rolling, heat treatment or welding. For example, chromium-molybdenum steel, so popular in airplane fuselage construction, does not (at least in the samples represented here) ever attain a high enough combination of strength and ductility to find a place in any of the merit tables. No engineer would, on this account, question the advisability of choosing the steel for the purpose mentioned.

It is also evident from the tables that no one type of alloy steel excels in all combinations of strength and ductility factors, but that nickel, chromium-nickel and chromium steels excel in a greater number of instances than any others. This is a confirmation of the choice of industry, since these three types of alloy steel are used far more than any others for structural work(12). In this connection one qualification should be made, namely, that chromium steel has third place by virtue of the effective showing of stainless iron in the Izod impact test, as indicated in Tables VII and VIII and in columns 7 and 8 in Table XIII. But the only Izod tests found in sufficient detail for comparative purposes were on stainless iron, medium-manganese steel and a few others, and while it is highly improbable that *any* steel would have excelled stainless iron in quality factors G and H, nevertheless the evidence at hand gives chromium-vanadium steel what should be considered as good a claim to third place in column 26 of Table XIII as chromium steel.

The so-called medium-manganese structural steel of from 1 to 1.75 per cent manganese finds a good place under quality factors G and H (Tables VII and VIII, based on tensile strength × Izod impact). But it does not have a high position under any of the quality factors based only on static tests. Its well-recognized value in railroad rails is thus explained, since here resistance to impact is the desideratum. Its use for bridges is doubtless explainable because of its much lower cost than the other structural steels here represented which have a higher merit value. A summary of the present approximate cost of the alloy steels here represented may be of interest at this point:

PRICES OF ALLOY STEELS

TYPE OF STEEL	DESIGNATION IN TABLES	PRICE PER POUND, CENTS
High-nickel-chromium steel	3E	50.00±
Stainless iron	5B, 5C	20.00±
3-per-cent nickel-chromium steel	3A, 3D	6.45
5-per-cent nickel steel	2A, 2C, 2F, 2I	4.90
3-per-cent nickel steel	2B, 2D, 2E, 2G, 2H	4.15
1½-per-cent nickel-chromium steel	3C, 3F, 3G	3.60
1-per-cent chromium-vanadium steel	6A, 6B, 6C, 6D, 6E	3.60
Mayari steel	3B	3.50±
2-per-cent chromium steel	5D, 5E, 5F	3.45±
Silico-manganese steel	9A	3.00±
½-per-cent chromium steel	5A	2.95
Medium-manganese steel	1A	2.90±

Silicon Structural Steel:

Some readers may comment on the absence of silicon structural steels in the comparison made in these tables. The reason for this is that one of the authors is engaged on an extensive compilation from the literature on silicon steels, and it was therefore thought best to omit this type. It may also be supposed that, probably, silicon structural steels would not have affected appreciably the conclusions in Table XIII. They are low-priced steels with somewhat higher combination of qualities than is found in carbon steel.

Some Outstanding Characteristics of Some of the Types of Steel:

It will be observed that the nickel steels owe their high standing in the various tables especially to a high elastic limit with high reduction of area, and slightly less to a high tensile strength. Thus the nickel steels stand well in Table XIII, columns 2, 4 and 5; and in columns 11, 12 and 13, where high tensile strength is the first essential; also in columns 17, 18 and 19, where again high elastic limit is essential. They likewise stand better in columns 20 and 21, where the elongations are not so high, than they do in column 22. But, in columns 24 and 25, their good elastic limits give them a better relative position even when greater elongation is demanded.

The chromium steels are characterized by a high percentage of elongation; this is especially true of the stainless irons, and of all the chromium steels when the drawing temperature is high. It will be noted that there is a relatively large proportion of the chromium and chromium-vanadium steels in prominent positions in columns 9 to 19, Table XIII, when the tensile strength is below 200,000 lb. per sq. in. or the elastic limit below 175,000 lb. per sq. in. Column 15 is, however, an exception. It will also be seen in columns 1, 3, 4, 22 and 25, where the elongation is influential, the chromium and chromium-vanadium steels are strong; whereas in column 2, where reduction of area represents ductility, they do not stand so well. Where a double influence is given to ductility, as in column 4, the chromium and chromium-vanadium steels stand much better than where the same figures are used with less emphasis on ductility, as in column 5.

The chromium-vanadium steels stand at the top when a high combination of strength and elongation is demanded, provided that very high strength is not essential. These high combinations are obtained by tempering at a high temperature. Compare columns 1, 3, 4, 9, 11, 14 and 17, Table XIII.

The chromium-nickel steels are predominant where reduction of area is important and elongation is not so influential; see columns 2 and 5. They also stand well when high elastic limit has a large influence, as in columns 3, 14, 15, 18, 19 and 23.

It will thus be seen that the chromium-nickel steels resemble the nickel steels, while the chromium-vanadium steels resemble those with chromium alone. In other words, the effect of the nickel rather overpowers that of chromium, while that of chromium is stronger than that of vanadium. This may, or may not, be due to the circumstance that in structural steels nickel is always more than 2½ times chromium, while chromium is always 4 to 5 times vanadium.

In conclusion, the authors would say that it is obviously necessary to make a start and it is hoped that the data and suggestions herein contained will be suggestive and provocative of discussion which may bring out the best figures extant. Those who are interested in each of the alloy steels studied will perhaps have material better than any we have selected. It is in this way that we hope to get further light on the problem, as well as any discussion of the methods of combining the figures to give comparative values of relative worth in different types of service.

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(10) James Riley, "Alloys of Nickel and Steel," *Journal*, Iron and Steel Inst., No. 1, p. 45 (1889).

(11) Henry M. Howe, "The Metallurgy of Steel," N. Y., 1889. Society Publishing Co.

(12) E. F. Cone, "Types of American Alloy Steels," *The Iron Age*, Vol. 124, December 26, 1929, p. 1735.

DISCUSSION

MESSRS. A. B. KINZEL[1] AND WALTER CRAFTS[1] (*presented in written form*).—We have gone over this paper in some detail, not only because of the unique method of presentation used, but also because of the extreme interest of any conclusions which may be drawn therefrom. The paper represents a very great deal of laborious effort on the part of the authors, and we are indeed pleased to see a step taken toward the solution of the ever-perplexing problem as to the relative merits of the various alloy steels.

In this work the authors use a number of quality factors to rate the steels in question, and the discussion of the results must needs bear on several points. The first of these is the matter of the significance of any quality factor. With certain rare exceptions, engineering practice in the past has used specifications of properties of steels for the purpose of duplicating the essential properties of a given material which has given satisfactory service in a given application. Thus, the matter of the given application is at once brought to the foreground, and any quality factor which does not take the application into consideration must be meaningless. The authors are undoubtedly aware of this, for they refer to a paper by one of the writers in which this matter is strongly emphasized, and in which it is pointed out that one logical way of evaluating the technical worth of the steel is by direct comparison of the various physical properties of the steel in question with those of the known steel in service, with proper weighting of the various factors involved, again depending upon the service. This is further illustrated by Tables I to VIII of this paper, in which, depending on the quality factor used, certain types of steel with similar heat treatments stand out as superior to others, and these types seem to run together in any given table. This means that the quality factors of Tables I to VIII really tell us little more than shown in the arrangement of Tables IX and X, in which the steels are grouped according to strength and then listed according to ductility. It would seem that the authors realized this condition and therefore included these tables.

The next point of interest is the data used for such tabulation. It is evident that where comparison is to be made based on absolute values which differ by only small percentages, it is essential that the methods of manufacture of the steel, mass of the heat-treated material, method of determining elastic limit and general accuracy of test data be identical or be given due consideration. That this has not been done is evident to us by the values which the authors have taken from a paper by one of the writers, as indicated in their reference(4). The figures quoted in this paper were on steels manufactured on a small scale and were given merely to establish the general order of the properties. Subsequent work with these steels in mill practice has shown that under commercial conditions higher values are regularly obtained. Moreover, on checking into the source of some of the other data it is evident that the values were obtained on single heats. It is well known that any given heat even with controlled analysis varies within certain limits, which are generally much wider than any differences shown between the best steels quoted in the Stoughton and Harvey paper. In order to obtain satisfactory data with this type of comparison, it is essential that a great many heats and a great many test samples be used and that the final figure be obtained according to some definite method of correlating these data. For example, the probable value or the maximum or minimum values independent of abnormal causal effect, could be used. It is appreciated that this is a stupendous task in itself, and we all know how many years the Society of Automotive Engineers has devoted to compiling data of this character. In view of this, the authors are not to be too severely criticized for using those data which were available to them in the literature, but it seems to us that they should emphasize this point in drawing their conclusions.

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It is unfortunate that the values on the silicon structural steels were omitted, as it would appear that the authors have very satisfactory data on these steels.

We regret that the authors felt it necessary to conserve space by not publishing the data and results which they accumulated on some of the more common structural steels, which in their compilation did not rate among the twenty best. In many cases, if this had been done, the difference between these steels and the maximum factor on the values actually published would, we are sure, be rather small. This is well illustrated by Table V, in which the difference between the twentieth and the first steel rated is only 10.8 per cent based on the elastic limit, elongation and reduction of area. This difference is less than would be expected within the normal variations of a series of one steel, even though the analysis were closely controlled. Moreover, in discussing structural steels the authors give undue weight to steels with more than 175,000 lb. per sq. in. tensile strength. The use of steels of such extremely high strength is very limited, indeed. That the authors have considered normalized steels, is evident from reference (7) to Jones' paper, in which no heat treated values are given. These steels naturally do not appear among the twenty best in any of the tables and should have been considered separately.

The matter of rating in each individual table is also of interest. The twenty steels rated the highest are listed, and these include steels of identical analysis with slightly modified heat treatment. This is well illustrated by Table II, in which the 0.20-per-cent carbon-chromium-vanadium steel is in the tenth line with a 840° F. draw, in the twelfth line with a 930° F. draw, and in the fifteenth line with a 1110° F. draw, and in which a nickel-carbon steel is in the second line with a 600° F. draw, and in the eighth line with a 400° F. draw. Had a 500° F. draw been available the steel would have been placed in approximately the fourth line and therefore nickel-silicon steel at the bottom of the list would have been omitted. If other drawing temperatures on the chromium-vanadium steel had been used, this would have occupied an intermediate position and still more of the steels, such as the 3.5-per-cent nickel and the 3-per-cent nickel, 0.75-per-cent chromium steel near the bottom of the list would not have been reported. On the other hand, if only the best drawing temperature had been used, it is quite probable that some of the other steels which have not been reported at all, such as the chromium-molybdenum steel, would find a place in the table. This situation is further aggravated by giving the first ten positions in the list a rating number from 1 to 10 and using this number in the compilation of the final data and in drawing final conclusions. The writers have attempted a different type of rating, using the figures as compiled by the authors. In this rating all steels in the table which are within 6 per cent of the maximum quality factor obtained are given a rating of 2, and all steels which are within 12 per cent are given a rating of 1. This seems to be a much more logical way than simply rating in order from 1 to 10, and the effect that it has on the final conclusions will be brought out later on in the discussion.

Tables IX and X are subject to the same general type of criticism as that applied to the tables above, with respect to the types of steel and different heat treatments used, and are open to the further objection that no consideration is given for variation in tensile strength or yield point within the group limit set. This is well illustrated by Table IX, in which the chromium-nickel steel at the bottom of the list with 6.3 per cent elongation and 292,000 lb. per sq. in. tensile strength is rated lower than the chromium-nickel steel with 270,000 lb. per sq. in. tensile strength and 8.7 per cent elongation. To all intents and purposes within the limits of accuracy of measurements and duplicability of the tests in question, these steels are identical in worth, yet in the rating the 292,000 lb. per sq. in. steel is rated eight and the 270,000 lb. per sq. in. steel is rated five, which as used in drawing the final conclusion rates one steel nearly twice as good as the other.

The method of summing up the data and drawing conclusions is open to serious question. Not only are the steels given ratings according to their order in the table, which in our opinion is illogical, but the figures for any one steel in each table are then added. Because the same data are grouped twice, once based on tensile strength zones, and once on percentage elongation zones, these data are given approximately twice the weight of those used in the quality factor tables. Moreover, depending upon the particular quality factor tables used, the weight given by these factors may be varied at will. For example, five tables are based on elastic limit, whereas only three of them are based on tensile strength. Thus, elastic limit is given 66 per cent more weight than ultimate strength, and this is probably a purely accidental occurrence, tending to further confirm the doubtful character of the final quality factor.

TABLE I.—SUMMARY OF RATING OF STEELS.

BY QUALITY FACTORS

Type of Steel	Table I	Table II	Table III	Table IV	Table VII	Table VIII	Total
Chromium-vanadium	2[a]	1[b]	2	1	..	..	6
High-chromium	2	..	2	2	2	2	10
Chromium-nickel	..	2	2	1	..	..	5
Nickel	..	2	1	2	..	..	5
Nickel-vanadium	..	1	..	..	..	..	..
Mayari	..	..	2	..	..	..	..
Silicon-manganese-chromium	..	..	..	..	..	1	..

BY STRENGTH ZONES

Type of Steel	Tensile Strength, lb. per sq. in., Table IX					Elastic Limit, lb. per sq. in., Table X						Total
	150,000 to 175,000	175,000 to 200,000	200,000 to 225,000	225,000 to 250,000	250,000 to 300,000	100,000 to 125,000	125,000 to 150,000	150,000 to 175,000	175,000 to 200,000	200,000 to 225,000	225,000 to 275,000	
Chromium-vanadium	2	1	2	1	1	2	1	1	2	2	1	16
High-chromium	2	2	..	..	..	1	1	2	..	1	..	8
Chromium-nickel	..	1	2	2	2	1	..	2	2	2	2	16
Nickel	..	..	2	2	2	1	2	1	2	2	2	16
Mayari	1	..	..	..	..	..	2	..	..	..	..	..
Nickel-vanadium	..	..	..	..	..	..	..	..	1	..	..	..

[a] 2 points for 94 per cent or better of maximum figure in each table.

[b] 1 point for 88 per cent or better of maximum figure in each table.

In order to show how the conclusions may be varied, the writers have drawn up the accompanying Table I, in which the individual rating of 2 and 1 were given on the basis of 6 per cent and 12 per cent of the maximum factor in each table, as previously explained, and in which

Tables IV and V are omitted, so that the identical numbers of ultimate strength factors and elastic limit factors are taken. It will be seen that based on this analysis the four most promising steels reported on in the Stoughton and Harvey paper are practically identical, as the writers believe that with this method of rating the difference between 5 and 6 is negligible. If we were tempted to draw any conclusions, 12-per-cent chromium steel would be rated first, chromium-vanadium second, chromium-nickel third and straight nickel fourth. This rating would not be affected by the inclusion of the ratings in Tables IV and V, which have been here omitted. This, of course, does not agree with the conclusions drawn from the data by Stoughton and Harvey. It is merely given here to show that with the data in question and the method of analysis used no such conclusions may be drawn, and further emphasizes the fact that many alloy steels will produce physical properties not only of the same order of magnitude but of such closely comparative values that the physical properties no longer become the dominating factor in the choice of a steel. Cost, reliability, uniformity, ease of manufacture, sensitivity to heat treatment, ease of machining and many other matters of direct interest to the steel maker and manufacturer outweigh any slight superiority in physical properties which one steel may have over another. That this conclusion is justified is further illustrated by the fact that steels of widely varying analyses are used in industry for practically identical applications, and that manufacturers change from one steel to another and back, even though the physical properties of these steels do not change.

In our opinion, in the 150,000 lb. per sq. in. tensile strength zone, in which the great majority of heat-treated structural steels may be classified, the quality factors obtainable with properly made, heat-treated, suitable carbon content low-manganese, chromium-manganese, silicon-manganese, chromium-silicon-manganese, chromium-molybdenum, nickel-molybdenum, nickel-vanadium and 2 to 6-per-cent chromium steels, would rate them in the same general order of magnitude as the four steels given the high rating in the paper. This is illustrated, first, by rating chromium-molybdenum steel according to the method used in the paper and, second, by using the system previously published by one of the writers, this system being based on comparison with service steels.

A well-known steel manufacturer has published the following values for heat-treated chromium-molybdenum steel with a 900° F. draw:

Tensile strength, lb. per sq. in.	185 000
Yield point, lb. per sq. in.	170 000
Elongation, per cent	18
Reduction of area, per cent	63

Using the quality factors in Tables I to VI of the paper, it is evident that this steel would head the list in Tables II, III and V and occupy positions 6, 2 and 4 in Tables I, IV and VI. Thus, this steel should certainly be included with the best steels reported. A similar count on chromium-manganese steel shows results of the same general order. If we consider a specific service, such as a steering knuckle in an automobile, in which static strength together with resistance to vibration and a certain amount of shock are required, we find that the following physical properties have proved satisfactory in service:

Tensile strength, lb. per sq. in.	150 000
Yield point, lb. per sq. in.	125 000
Elongation, per cent	20
Reduction of area, per cent	58

The following equation has been developed for comparing steels subject to this type of service:

$$\frac{w}{W} = \left(\frac{y}{Y}\right)^{\frac{1}{3}}\left(\frac{u}{U}\right)^{\frac{1}{2}}\left(\frac{e}{El}\right)^{\frac{1}{3}}\left(\frac{r}{R}\right)^{\frac{1}{3}}$$

In this equation, R is the following function of the reduction of area:

$$R = \frac{100\ RA}{100 - RA}$$

The first comparison will be with the chromium-vanadium steel with representative values as follows:

Tensile strength, lb. per sq. in.	150 000
Yield point, lb. per sq. in.	120 000
Elongation, per cent	22
Reduction of area, per cent	60

Substituting in the formula we find that this steel is 2 per cent more satisfactory, based on the representative values here used. It is obvious that the difference is negligible. Compare a 3-per-cent chromium steel with the following values:

Tensile strength, lb. per sq. in.	165 000
Yield point, lb. per sq. in.	155 000
Elongation, per cent	16
Reduction in area, per cent	55

We find that this steel has exactly the same worth as that of the representative steel chosen for a basis of comparison. Thus, it is obvious that this steel should be listed with the best steels cited in the paper. Calculations based on the properties of the other steels listed above will show that they too should be included with the best steels mentioned.

MR. H. C. KNERR[1] (*presented in written form*).—The paper of Stoughton and Harvey obviously represents a very large amount of work and is of a type which will probably become more and more important in engineering efforts, namely, the classification and interpretation of accumulated data. It would be difficult and hardly fair to attempt to discuss the paper without giving it the extended study which it deserves, but the following comments are offered as representing the reactions of one reader.

A primary difficulty, as the authors have mentioned, is to decide upon a basis of merit classification. To take a variety of merit or quality factors, tabulate the results under each, and add up the total points is likely to be misleading because a large proportion of the merit factors might be of no value from the standpoint of certain uses. There is of course no "one best steel," but for each purpose or combination of circumstances, one steel or composition may be superior to others. It is believed, therefore, that it would be preferable first to set up a quality factor, taking into consideration all of the important features desirable in steel for a certain purpose, then to classify various steels for this purpose. For example, the machineability of a steel is an important factor determining its usefulness. This again must be classified under two headings, machineability in the annealed state, when the part is to be subsequently heat treated, and machineability in the heat-treated state, where the raw material is heat treated prior to machining.

It is not believed that the combination of any two or even three factors is sufficient for a quality classification. A steel having a high tensile strength and elongation might have a low yield point. For automobile and aircraft a high fatigue value is necessary. Impact value is important, but aside from a distinct tendency toward brittleness, in steel having low impact value, it is difficult to find evidence that variations in impact value between medium and high have any direct relation to the serviceability of steel.

In considering merit factors it is interesting to note that piano wire, which is one of the most remarkable of materials of construction, having a tensile strength as high as 400,000 lb. per sq. in., and great toughness as evidenced by the ability to stand severe direct or reverse bending, has a very low measured elongation and an elastic limit which is difficult to determine.

In observing the values given in the tables, the question arises how representative they are of the various types of steel. In other words, do some of the high values represent freak instances?

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[1] Consulting Metallurgical Engineer; and President, Metallurgical Laboratories, Inc., Philadelphia, Pa.

The fact that chromium-molybdenum steel is missing from the classification is difficult to accept by those who have had experience with this remarkable material. Chromium-vanadium steels, in composition Nos. 6130 and 6150, appear frequently with high ratings. Chromium-molybdenum steel has properties very similar to those of chromium-vanadium, and in the experience of some, certain advantages such as better machineability in the heat-treated state, better cold drawing properties, better weldability, etc. It may be that this steel has not appeared in the classification because it is ordinarily used in the form of thin sheet or tubing, in which the elongation values are influenced by the form and thickness of the test specimen. The following values are believed conservative for bar stock:

Tensile strength, lb. per sq. in.	200 000
Yield point, lb. per sq. in.	180 000
Elongation in 2 in, minimum, per cent	12

These values would take a place well up among the first ten classified.

In order to simplify calculations and comparison of values, it is suggested that strength values be taken in thousands of pounds per square inch. There is no advantage in going beyond the third place in decimals, as strength data are seldom accurate beyond one per cent, while elongation values, used as a denominator, or otherwise, are rarely within this accuracy.

The paper is a valuable step toward greater simplification but it is believed that generalities may be taken from it only with great care.

MR. E. J. JANITZKY[1] (*presented in written form*).—The paper by Messrs. Bradley Stoughton and Wilber E. Harvey on merit indices of alloy steels with respect to mechanical properties is certainly interesting inasmuch as it focuses attention on a comparison of physical properties of alloy steels. However, the fact that a particular steel does not have the same ranking under each quality factor used by the authors clearly indicates the inadequacy of one or all of these factors to depict the true relationship of one alloy steel to another. There has been no classification of results in accordance with the section treated or with the quenching temperature used (as it relates to the critical temperature) and yet these two factors vitally affect the physical properties of heat-treated steels. The writer presents herewith a quality factor for heat-treated pearlitic steels which fully accounts for all these variables.

The formulas and curves are based on data from a variety of steels obtained principally from cooperative results collected by the

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[1] Metallurgical Engineer, Illinois Steel Co., Chicago, Ill.

Society of Automotive Engineers, from published British data and from laboratory work of which the writer had charge.

The basic equation for the merit index is:

$$n = \sqrt{\frac{(T - Y)(E + R)}{1000}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which T, Y, E and R represent the tensile strength, yield point, elongation and reduction of area expressed in the usual units of pounds per square inch and of percentage, respectively, and n is the merit index. When pearlitic steels are heat treated to develop their maximum ductility for a given tensile strength this merit index equals 30 ± 4. Alloying elements primarily counteract mass effect in quenching and the present-day S.A.E. steels contain the requisite alloy content to yield maximum ductility when correctly heat treated in 1-in. sections. Thus all pearlitic steels properly quenched in 1-in. rounds to yield the finest grain structure will have the same merit index regardless of the drawing temperature. In other words, although it is true that various alloy steels, given identical heat treatment, will yield unlike tensile strengths, elongations, etc., yet when the same steels are correctly heat treated in sections of 1-in. rounds or less so as to yield equal tensile strengths, their yield points, elongations and reductions of area will be identical. The quality factor n thus indicates whether a heat treatment used has been inadequate to yield maximum ductility with a given tensile strength. Such inadequacy results from too high or too low a quenching temperature, yielding too coarse a grain structure, or from too large a section to obtain thorough quenching penetration or from too low an alloy content for the section used. Although the quality factor n is not capable of interpretation as to which of these factors is the cause of the inadequacy of development of maximum ductility, n can be used to enumerate the efficiency of the heat treatment by the following equation (giving the percentage of perfection):

$$n = \frac{3000}{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The efficiency of the heat treatment is 100 per cent when n is 30 and is less than 100 per cent when n is greater than 30. When a steel is under discussion of which the alloy content and section are known to be sufficient to give a quality factor 30 after proper heat treatment, the various physical properties can be determined in advance by the following formulas:

$$T = B\,\frac{1000}{2.1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$E = \frac{2{,}500{,}000}{T} \quad \ldots\ldots (4)$$

$$R = 100 - \frac{100}{\left(\frac{E}{30} + 1\right)^2} \quad \ldots\ldots (5)$$

$$Y = T - \frac{1000 \times 900}{R + E} \quad \ldots\ldots (6)$$

in which T, Y, R and E represent terms as used in Eq. 1 and B is the Brinell hardness number (with 3000-kg. loading). Thus if an alloy steel, with section and analysis known to be correct for obtaining a 100-per-cent efficiency of heat treatment, be desired heat treated to a specific Brinell hardness number, the physical properties which will be obtained can be evaluated from Eqs. 3 to 6.

It is especially interesting to note the authors' attempt to relate tensile strength with Izod impact values, but here again mass effect, the most vital factor, has been neglected in their correlation. The writer has also developed a relationship between the tensile properties and Izod impact value which, as does the quality factor n, accounts for the effect of mass and of quenching temperature. It is a practical observation that tensile strength is inversely proportional to the Izod impact value for certain sections but that the two properties are directly proportional in larger masses. Equations giving this relationship are:

$$I = \frac{10\,E^2}{R} \cdot \frac{d}{30} \quad \ldots\ldots (7)$$

for steels whose factor T/Y is less than 1.2, d being obtained from Eq. 5 by rewriting it as:

$$R = 100 - \frac{100}{\left(\frac{E}{d} + 1\right)^2} \quad \ldots\ldots (5\,a)$$

and

$$I = \frac{Y^2}{1000\,T} - 5 \quad \ldots\ldots (8)$$

for steels whose factor T/Y is more than 1.2, in which I represents Izod impact value. This relationship is readily understood by referring to the accompanying Fig. 1, where curve AB represents the relationship between tensile strength and Izod impact value for S.A.E. steels which, when heat treated, show less than 100-per-cent efficiency due to improper quenching temperature, insufficient alloy content or incomplete hardness penetration, and curve *CAD* for S.A.E. steels which show 100-per-cent efficiency of heat treatment.

This presentation, it is believed, indicates more clearly than the authors have shown, that the action of alloying elements primarily counteracts the effect of mass during quenching and that in order to yield usable conclusions a quality factor for comparison of alloy steels must take into account the mass of the material considered.

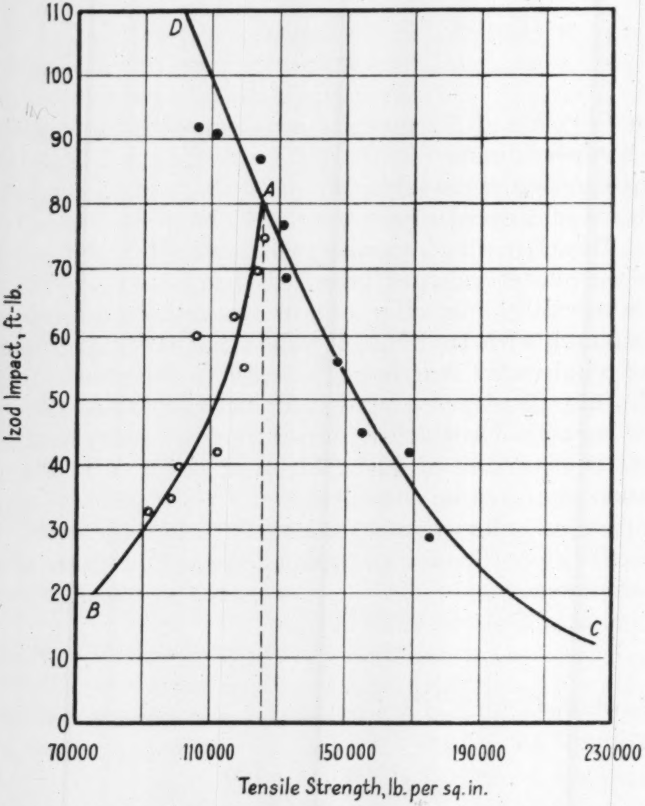

FIG. 1.—Relationship of Tensile Strength and Izod Notch Toughness for S.A.E. Steels Heat Treated in Various Sections and by Various Treatments.

MR. E. E. THUM[1] (*presented in written form*).—I have admiration for the industry with which the authors have pursued their investigations on the subject of the merit index, yet I believe that the net result of the work is to confirm the suspicion already held in many minds that the suitability of steel for diverse services can seldom be accurately appraised by tension and impact tests. This is said with no thought of disparaging the importance of physical testing for the control of plant operations, or for the purchase of material, or even for developmental studies in research laboratories. I do mean to say, however, that such tests all too frequently fail to indicate what the result will be in actual service.

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[1] Associate Editor, *The Iron Age*, New York City.

For instance, the tension test is wholly incapable of indicating the relative suitability of metals for railroad rails or for knife blades. Lest it be suggested that these are unusual applications of the test, I could point out that certain heat-treated bridge wire which had superior physical properties when measured by tension, torsion and bending tests, and which by most of the merit indexes discussed by Stoughton and Harvey would be graded higher than the conventional cold-drawn patented wire, yet which failed most expensively in actual use and at a very low unit stress. You do not need to be reminded that suspension bridge wire acts in as nearly pure tension as can be imagined for any structural member.

A further illustration of the unreliability of the so-called merit index for making a quantitative comparison of various steels may be drawn from the four well-known structural steels shown below:

	NICKEL STEEL	MEDIUM MANGANESE STEEL	STRUCTURAL SILICON STEEL	ORDINARY STRUCTURAL STEEL
COMPOSITION:				
Carbon, per cent	0.38	0.33	0.35	0.20
Silicon, per cent	....	0.18	0.27	....
Manganese, per cent	0.58	1.63	0.78	0.50
Nickel, per cent	3.45	....	....	....
TENSILE PROPERTIES:				
Tensile strength, lb. per sq. in.	99 850	101 600	87 000	58 600
Yield point, lb. per sq. in.	60 250	58 600	49 300	36 400
Elongation in 8 in., per cent	17.9	19.5	21.6	27.4
Reduction of area, per cent	53.3	42.6	42.1	....

The data for the $3\frac{1}{2}$-per-cent nickel steel is the average of a large number of tests of the steel used by J. A. L. Waddell in the St. Louis bridge. The data for the medium-manganese steel is the average of the nearly 1000 tests on steel for the Kill van Kull arch and the data for the silicon steel is the average of about 600 tests on steel furnished for the Hudson River suspension bridge, both furnished by O. H. Ammann, chief engineer of bridges for the Port of New York Authority. The physical data for the carbon shapes are averages from Mr. M. O.

Withey's tests on specimens cut from different portions of structural steel shapes, presented to the 1928 meeting of this Society.[1]

Tensile strength and yield point in the annealed or as-rolled condition are substantially the same for the 3½-per-cent nickel steel and the 1½-per-cent manganese steel (approximately 100,000 and 60,000 lb. per sq. in., respectively), but the former has a superior reduction of area while the latter has a superior elongation in 8 in. Therefore, any merit index which emphasizes the percentage elongation (such as quality factors "A" and "C") will show that manganese steel is superior to nickel steel, whereas any formula which emphasizes the reduction of area (such as quality factors "B," "D," "E," and "F" of the present paper) will indicate that the nickel steel should take first place. Furthermore, a computation of all the quality factors mentioned by Stoughton and Harvey will show that according to one criterion the best of these four steels is only 14 per cent superior to the worst, whereas the spread is 50 per cent according to another merit index!

Brief consideration of the commercial and engineering use of the structural steels discussed above makes it apparent that many things besides the tensile and impact strengths will influence the engineer in making his selection. Cost is the ruling factor in practically every instance. Cost is a total of a large number of items having little relationship to tensile and impact strengths. Mr. C. E. Chase, principal assistant engineer of the Delaware River suspension bridge, has stated that 3¼-per-cent nickel steel could be used on that bridge because a large amount of scrap armor plate was on the market and could be used in its manufacture. At that time nickel steel cost only 11 per cent more than silicon steel, yet it was stressed 22 per cent higher. On the other hand, when bids came in for the Hudson River bridge the price for nickel steel was about 24 per cent higher than silicon steel, since the stock of cheap raw material was no longer available. On that basis nickel steel and silicon steel would be about equivalent, unless the nickel steel could be stressed even higher than it had been in the past, or unless large savings through collateral advantages could be expected.

To stress this point further, it is well known that the arch bridge over the Kill van Kull was bid on the basis of conventional 3¼-per-cent nickel steel but actually is being erected of medium-manganese steel. A substantial reduction in cost was possible, representing the sum of several different factors.

As was so well said by Mr. C. F. W. Rys in a recent meeting of the American Iron and Steel Institute, nickel steel will be the first choice of well-informed engineers when the maximum of ductility, resistance to shock and to alternate stresses is required in combination with good strength and elastic limit. This reputation of nickel steel is based not upon tensile tests or merit indexes but upon a long and honorable history wherein it has exhibited the utmost reliability in the most difficult service.

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[1] M. O. Withey, "Tests of Specimens Cut from Different Portions of Structural Steel Shapes," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 41 (1928).

MR. H. J. FRENCH[1] (*presented in written form*).—From time to time attempts have been made, through so-called "merit factors," to evaluate the mechanical properties of steels in such a way as to indicate their usefulness for various classes of service but in most of these surveys not more than one or two methods of comparison have been employed. The authors of this paper have rendered a service in bringing together for comparison the results obtained by many methods of evaluation.

Since, as has been pointed out by the authors themselves, the requirements vary for different classes of service those who study this paper may favor one or another of the quality factors or possibly suggest others, depending upon their individual interests or viewpoints. By the same token, it is not to be expected that any one method of comparison can serve all purposes and it is by summaries such as have been given in this paper that the several methods of evaluation can themselves be more justly appraised.

The recapitulation in Table XIII is of particular interest in that it takes into account all of the "merit factors" considered and provides a basis on which to judge the scheme of classification proposed by the authors. The superiority of the nickel and nickel-chromium steels shown in Table XIII is entirely consistent with industry's appraisal of these steels both as regards the character and the extent of their applications and may be considered to indicate the usefulness of the authors' classification.

One matter of importance is the effect of size on the mechanical properties obtainable by heat treatment. If the sections considered become appreciably larger than those of the customary test bar sections some of the low-alloy steels in the group studied would not be capable of giving very high strengths and would be eliminated from at least some of the comparisons. Of course this does not vitiate the comparisons given by the authors but suggests the need of carrying the work further.

It is doubtful whether a quantitative evaluation can be secured to cover all of the features to be considered in the industrial applications of alloy structural steels due to the customary complexity of service requirements. However, it would seem that the plan advanced by the authors should be helpful in providing a classification consistent with industry's appraisal of certain of the mechanical properties of the steels considered.

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[1] Metallurgist, Development and Research Department, The International Nickel Co., Inc., Bayonne, N. J.

MR. JEROME STRAUSS.[1]—While comparisons of this nature may have at times some value, I believe it is essential that we consider two points in attempting to obtain such comparisons. The first is that we have strictly comparable data, and the second that we weight that data in some consistent manner. More specifically, when one takes data from the literature concerned with the elastic limits of steels, he may secure values which are elastic limits or proportional limits or Johnson's limits or yield points; and when one examines heat-treated or un-heat-treated alloy steels, he will find that the closeness of these various "elastic" values varies very greatly with the material and the heat treatment, and consequently cannot be used interchangeably. I wish also to call specific attention to the impact values the authors have employed; the values on the manganese steels were obtained with Izod test bars having cylindrical notches of 2 mm. diameter; the values for the other materials were secured with the usual 45-deg. V notch. The former gives higher values and the extent to which they are higher varies with the material and with the heat treatment. If all of the data recorded had been secured in the same manner and if all of the steels studied had had impact values available, the pearlitic manganese steel would not have appeared in the individual tables.

It is also important, as Messrs. Kinzel and Crafts have brought out, to use the same number of similar observations for all of the steels. Obviously the inclusion for one steel, of for example, half a dozen values within the tensile strength range of 200,000 to 250,000 lb. per sq. in. one value in the range of 75,000 to 100,000 lb. per sq. in., and for another steel six within the latter range and one within the former range, will appreciably influence the meaning of the computations. The authors have rated their first ten steels by the assignment of values of one to ten according to their position in their particular arrangement. But the use of alloy steels, as brought out by the authors, is based on a number of considerations, and principal among these are the various fabricating qualities, the mechanical properties obtainable, and, to a very important measure, their reliability as expressed by the ability to produce a given physical state in the final product within a narrow range of variation or, putting it another way, using a specific composition range and a defined processing specification, one desires to secure a definite physical condition which will, over a long period of testing, show a very narrow loop on a frequency curve. Consequently, instead of using the rating advocated by the authors in assembling their final table, some scheme should be employed which shows the difference between the actual individual merit indices obtained for different steels in different conditions and the maximum which was secured for that particular type of index. It may be mentioned in this connection that we also prepared an analysis of the data as Mr. Kinzel did, only using different limits, and obtained still a different answer.

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[1] Chief Research Engineer, Vanadium Corporation of America, Bridgeville, Pa.

MR. R. S. JOHNSTON.[1]—The authors have asked for suggestions for a quality factor. I think that in the structural engineering field today there is a real need for a quality factor. We have been designing in carbon steel. We are working now into the higher alloy steels—riveted tension members as an example. There are local overstrains around rivets that cause very high periphery stresses. We have had no trouble with carbon steels; they are able to re-distribute such local over-stress. I do not think that condition holds with some of the higher strength structural steels. We need some measure, therefore, from the structural engineering standpoint at least, that will differentiate the steels and tell us whether we have a steel which will meet local overstrain and re-distribute it.

Another example of the condition I have in mind is brought out in connection with the construction of rotors for generators. It has been found in England, I know, and there was a paper before the recent engineering congress in Japan, that called attention to the fact that highly stressed and strained alloy steels do not give as good service at high periphery speeds as a carbon steel which has been run 50 per cent overstrain in a bomb proof and then re-bored for use. The alloy steels fly to pieces; the overstrained carbon steel give satisfactory service.

There is, therefore, I believe, a vitally important necessity for the development of some criterion or quality factor or whatever you want to call it, that will differentiate these steels and permit us to determine when we have a steel that will relieve local overstrains and act safely, and when we have one that will crack, and, because of its intrinsic strain, suddenly break.

MR. WILBER E. HARVEY.[2]—The authors wish to express their appreciation of the cooperation of those who have discussed the paper in an attempt to correlate some of the existing data on the mechanical properties of alloy steels.

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[1] Director of Research, John A. Roebling's Sons Co., Trenton, N. J.

[2] Instructor, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

The predominant comment seems to have been the selection of data for the computations. It is to be expected that the maximum results would not have been selected in every type of steel since they would not be available in one collection of data. It is our regret that the best values for each steel were not available to us and our computations were made from the data at our disposal. For a future paper we invite the best data available.

The intangible factors such as the measurement of machineability were not used in computation although machineability is an important detail in the selection of a steel. Some alloy steels are machined in the annealed state and then hardened, others can be hardened and then machined. A method of weaving machineability into quality factors would be welcomed, as well as one including the price of alloy steels.

Messrs. Kinzel and Crafts suggested that we have the same heat treatment of steels following once or twice in the same table with our quality factors. I would like to answer that, if we choose quality factor A, which is a product of the tensile strength times the elongation, we have two variables, the tensile strength and the elongation. If we take a steel and give it a low draw, such as 400° F., we find the tensile strength is high and the ductility low, and if we increase the temperature of the draw we find that the ductility has been increased and the tensile strength decreased. It is the product of those factors which we sought, and that accounts for our using it more than once in our final tables.

We realize that our offering is a pioneer in its field and hope that it will urge more and better papers toward the evaluation of alloy steels.

MR. J. M. LESSELLS[1] (*by letter*).—The paper by Messrs. Stoughton and Harvey represents a great deal of labor but it is very doubtful if such work can be altogether justified. It is quite true that any work which allows grading of different kinds of steels in order of usefulness is valuable to the designer but we must take care not to mislead him.

In using physical test values as a basis for design we must keep in mind which tests are really fundamental and which quite arbitrary. The ultimate strength obtained in the tension test is fundamental in that the value obtained can be used directly as the basis of working stress for static conditions. Similarly, with dynamic conditions, the endurance limit can be used and in that sense is also fundamental. With these values quite a large number of machine parts can be safely designed.

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[1] Manager of Mechanics Division, Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

With regard to impact conditions, we are not on secure ground. Very little is known as to what impact values really mean. They are quite arbitrary in nature and with our present knowledge can only be used as a criterion of satisfactory heat treatment. The same thing applies to elongation and reduction of area values obtained in the tension test. We do not know at present what amounts will justify us in classifying one material as brittle and another as ductile.

In view of these points, in the writer's opinion, it is entirely misleading to multiply such values as "elastic limit" and "elongation" or "tensile strength" and "Izod impact." What we want is simplification and a better understanding of what these arbitrary values mean.

MESSRS. BRADLEY STOUGHTON[1] AND WILBER E. HARVEY[2] (*authors' closure by letter*).—The discussion presented by Messrs. Kinzel and Crafts involves many points of especial interest to anyone acquainted with alloy steels and their makers. Their discussion represented many well-directed efforts toward a "clearance" of alloy steel troubles.

Messrs. Kinzel and Crafts regret "that the authors felt it necessary to conserve space by not publishing the data and results which they accumulated on some of the more common structural steels, which in their compilation did not rate among the twenty best." The authors also regret that these values were not published, but they view sympathetically the practice of technical societies in minimizing publication as far as possible.

It will be seen by reference to page 255 of the paper that Messrs. Kinzel and Crafts' statement to the effect that the authors might have very satisfactory data upon silicon structural steels, had already been answered by them with the note that, probably, silicon structural steels would not have affected appreciably the conclusions in Table XIII.

It is rather difficult to realize Messrs. Crafts and Kinzel's objections to too much attention being placed upon structural steels with a tensile strength of 175,000 lb. per sq. in. or better. It is quite well known that the cable wires for most of the new suspension bridges have a minimum strength specification of 225,000 lb. per sq. in. Other structural units likewise have high stress values and the trend in structural steel development is toward higher strength steels.

Messrs. Kinzel and Crafts have computed a table which arranges the alloy steels in a different order than the one published by the authors. In their table, individual ratings of 2 and 1 were given to steels on the basis of being within 6 per cent and 12 per cent of the maximum value obtained for the leading steels. According to their conclusions 12-per-cent chromium steel would be rated first, chromium-vanadium second, chromium-nickel third, and straight nickel fourth. Just why Messrs. Kinzel and Crafts chose limits of 6 per cent and 12 per cent is not apparent since Mr. Jerome Strauss in his discussion indicates that he had made calculations similar to those of Messrs. Kinzel and Crafts using different limits only and again arriving at results different from either of the other tables.

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[1] Professor in Charge, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

[2] Instructor, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

Messrs. Kinzel and Crafts in order to reduce the tensile strength - elastic limit ratios of 3 to 5 to 3 to 3 have chosen to omit Tables IV and V in their calculation with the statement that their ratings would not be affected by the inclusion of the data contained in the omitted tables. Again, just why Tables IV and V were omitted is not very apparent since to equalize the tensile strength - elastic limit ratio, any other two tables which included the elastic limit might have been omitted with a still different result. It is not the authors' belief that the ratio should be equal. It is far safer to design structures on elastic strength than on the breaking load and it was not unintentionally that the 3 to 5 ratio occurred.

We agree with Mr. Knerr that there is no one best steel for all purposes or combinations. On the other hand, in a series of steels which, for example, will machine with reasonable facility and economy, the one having the best combination of mechanical properties would be the best to choose. Mr. Knerr speaks of the importance of a high fatigue value and we want to point out that the latest researches seem to indicate that the fatigue value is a direct function of the tensile strength, and, therefore, at least some of the quality factors which we have suggested will meet this condition. One of the objects of our paper was to try to get from interested people a series of representative values of the different types of alloy steels. We endeavored to choose our values on a representative basis and we assuredly tried to avoid any of the so-called "freak" values to which Mr. Knerr refers. We are very much disappointed that more of the able authorities in this field who have discussed the paper did not accept our suggestion by offering representative values such as we have been seeking. We are very grateful to Mr. Knerr for the values he has given, but regret that he does not also include a representative figure for reduction of area.

We are, of course, very familiar with the splendid work done by Mr. Janitzky and are pleased that he has added some information to the subject which we have here advanced. We believe, however, that the suggestions he has made for quality factors, while certainly of great value in the field which he mentions, would not be suggested by Mr. Janitzky himself for the type of steels to which our discussion was necessarily limited, namely, the structural and spring steels. We are sure that Mr. Janitzky's suggestions will form a valuable addition to this subject and would be an important check on the heat treatment of steels, but would not be applicable as a quality factor for alloy steels in general.

We think that the example given by Mr. Thum for heat-treated bridge wire argues against the conclusion which he has drawn, since it is now known that the heat-treated wire had actually had a part of its elastic strength fade out of it before it was put in service. Mr. Thum brings out very strongly a fact which we also tried to emphasize, namely, that the different quality factors do not all express the same facts. The problem before us is to find which one is the best for any one type of service of steel. Mr. Thum concludes his discussion with a very high encomium on a certain alloy steel which he says is not based on merit indexes but on a long and honorable history and service and the opinion of well-informed engineers. We want to point out that according to several of the merit indexes which we have suggested, the same steel stands out as superior to the others. This in itself is a very definite argument in favor of trying to work out some quality factor which may perhaps still more accurately represent actual facts in service. We had not attempted to find a factor which could be known in advance to check with experience, but it happens that the factors which we have chosen on the basis of certain arguments, which are given in the paper, do in many cases confirm the results of long experience.

Mr. Jerome Strauss has suggested that proportional limits may have been used interchangeably with elastic limit values. This substitution was made in but a very few places where the proportional limit was available and the elastic limit unavailable. In each substitution the substituted values were very clearly marked with an asterisk indicating a footnote calling attention to the substitution.

Mr. Lessells indicates that the terms or values such as "elastic limit," "elongation" and "tensile strength" have nothing but an arbitrary value at best. It is quite necessary that some things be accepted in order that a foundation be laid for future progress. These so-called "arbitrary" elastic limit, elongation and tensile strength values have been used extensively in design problems and have thus far been satisfactory. At least they represent the best values and definitions that the structural engineer has at his command at the present time.

SOME EFFECTS OF NICKEL CONTENT IN AUSTENITIC IRON-CHROMIUM-NICKEL ALLOYS

By Norman B. Pilling[1]

Synopsis

The chromium-nickel "stainless" alloys which are now drawing the attention of both the engineering world and the general public have certain undesirable properties which at times interfere with their fullest application. They include such qualities as: excessive hardening on cold working, poor fabricability, loss of ductility both cold and at moderately high temperatures, loss of corrosion resistance, and weld decay. The paper shows that much of this is due to a physical instability characteristic of certain austenitic alloys. The range of composition subject to this trouble has been mapped out, thus affording a new basis for the proper proportioning of stainless alloys.

On this basis, the present popular 18 per cent chromium, 8 per cent nickel type of alloy is compared with a typical example of the new proportions, the comparison including both physical, working and corrosion-resistant properties.

The development of the "stainless" type of iron alloy, in which many individuals the world over have participated during the past two decades, has reached a stage in which the interest of both engineers and producers is to a very large extent focussed upon the austenitic alloy containing about 18 per cent of chromium and 8 per cent of nickel. The many useful properties and comparative merits of the austenitic and non-austenitic types will not be touched on, but it is proposed to examine in this paper some characteristics of the austenitic iron-chromium-nickel alloys bearing on the utility of the 18 per cent chromium, 8 per cent nickel composition. It will be shown that the group of compositions commonly described as "austenitic" should properly be split into two groups, a "marginal austenitic" group and a "stable austenitic" group. As the designation implies, the latter has qualities of permanence which the marginal alloys do not have; the popular 18 per cent chromium, 8 per cent nickel composition lies within the range of "marginal" alloys.

These abstractions will become clearer by reference to Fig. 1. This diagram shows the relation between structural composition at ordinary temperatures and chromium-nickel contents. Such a diagram is very useful for indicating general features in small compass, but it is inexact, for by virtue of the compression which makes it valuable, it must suppress the effect of other conditions of importance, in this case carbon content, heat treatment and conditions of equilibrium at higher temperatures. However, annealed alloys of low-carbon content are martensitic (hard, magnetic, responsive to heat treatment) when their nickel-chromium contents locate them to the left of curve 3; they are austenitic (soft, non-magnetic, unresponsive to heat treatment) when their composition is to the right of curve 3. In the discussion which follows, some of the evidence will be given which indicates that those austenitic alloys lying in composition between curves 3 and 4, while austenitic by ordinary tests, are yet subject to a structural change under certain conditions, with changes in properties which may have importance.

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[1] Metallurgist, International Nickel Co., Bayonne Laboratory, Bayonne, N. J.

TABLE I.—NOMINAL MARTENSITIC LIMITS.

Alloy	Analysis			Brinell Hardness (3000-kg. Load)		
	Nickel, per cent	Chromium, per cent	Carbon, per cent	Oil Quenched from 1000° C.	Air Cooled from 1000° C.	Furnace Cooled from 1000° C.
No. 1	26.0	nil	0.02	227	231	232
No. 2	27.9	....	0.02	103	106	95
No. 3	16.6	4.9	0.02	277	275	284
No. 4	18.7	5.0	0.05	116	110	112
No. 5	10.6	10.0	0.05	321	309	304
No. 6	12.9	9.8	0.09	127	125	124
No. 7	7.9	14.6	0.17	180	164	167
No. 8	9.0	15.2	0.07	163	148	157
No. 9	7.0	20.4	0.08	188	186	202
No. 10	5.1	20.5	0.11	229	265	313

TABLE II.—CHEMICAL COMPOSITION OF A GROUP OF ALLOYS STUDIED.

Alloy	Nickel, per cent	Chromium, per cent	Carbon, per cent	Silicon, per cent	Manganese, per cent	Copper, per cent
No. 11	20.65	5.05	0.04	....	....	....
No. 12	22.22	4.98	0.08	....	....	....
No. 13	24.41	4.80	0.07	....	....	....
No. 14	20.71	7.92	0.43	1.13	0.19	....
No. 15	24.02	8.45	0.50	2.89	0.84	1.81
No. 16	12.80	17.30	0.18	0.26	0.76	1.83
No. 17	12.66	13.44	0.22	0.29	1.00	2.31
No. 18	15.46	15.04	0.23	0.19	0.81	....
No. 19	10.33	15.57	0.12	0.38	0.41	....
No. 20	8.06	17.65	0.14	0.34	0.17	....
No. 21	7.00	19.82	0.16	0.59	0.50	....

STABLE AND UNSTABLE AUSTENITIC ALLOYS

The limits of the range of martensitic alloys were traced at an early date by Strauss;[1] his limit is indicated by curve 1 in Fig. 2. A more recent determination in the laboratories of The International Nickel Co., for alloys of about 0.1 per cent carbon content or less is shown by curve 2. This limit lies at appreciably higher alloy contents than that of Strauss. Brinell hardness measurements (checked by a magnetic inspection) of the bracketing compositions indicating the first appearance of martensite are given in Table I.

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[1] Benno Strauss, "Non-Rusting Chromium-Nickel Steels," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 208 (1924).

The fact that austenitic compositions not very far removed from curve 2 (Fig. 2)—identical with curve 3, Fig. 1—will change, partially at least, to martensite or some similar alpha-iron phase under the proper stimulus has been evident for some time. Many who have handled the early 18 per cent chromium, 8 per cent nickel alloys having carbon contents considerably greater than that striven for today have been impressed by the rapid increase of hardness and the very great increase in magnetic permeaability which they developed after even a moderate amount of cold working. Hatfield showed[1] that this change is associated with the appearance, on the X-ray spectrogram, of an alpha pattern previously absent. It may be tentatively assumed that the change occurring is the precipitation and coalescence of some alpha-iron phase, perhaps further complicated by a carbide precipitation.

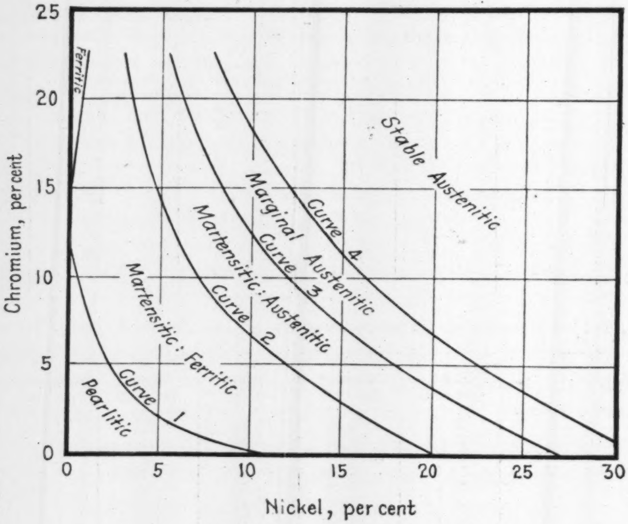

FIG. 1.—Constitutional Diagram of Low-Carbon Iron-Chromium-Nickel Alloys.

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[1] ***Engineer*** (Metallurgical Supplement), October 30, 1925.

This instability occurs only in alloys whose major composition locates them near curve 2 in Fig. 2. This range of alloys and its limits have been studied with a group of about a dozen melts, listed in Table II. It was found that the formation of alpha-iron was aided by (1) heating within the temperature range 600 to 900° C.; (2) plastic straining and most intensely (3) straining following heating at about 700° C. These conditions were realized experimentally by heat treating and breaking tension test specimens. A magnetic

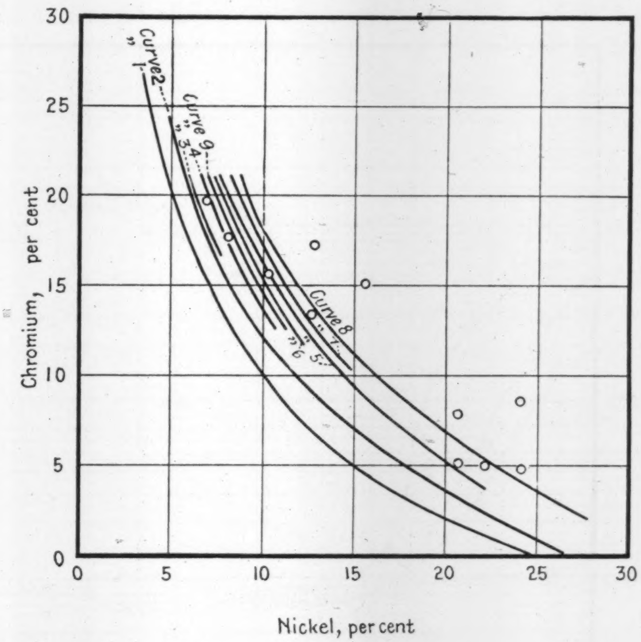

FIG. 2.—The Unstable Austenitic Range.

Curve 1.—Strauss		
Curve 2.—Limit of Martensite Range Determined by Brinell Hardness Number	Oil Quenched at 1000° C.	
Curve 3.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 1200° C.	Not strained
Curve 4.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 800° C.	Not strained
Curve 5.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 700° C., 24 hours	Not strained
Curve 6.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 1200° C.	Fractured
Curve 7.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 800° C.	Fractured
Curve 8.—Limit of Martensite Range Determined by Magnetic Inspection	Water Quenched at 700° C., 24 hours.	Fractured
Curve 9.—Limit of Martensite Range Determined by Magnetic Inspection	Air Cooled at 1000° C.	Cold Rolled

inspection with a small sensitive magnet was used to detect the presence of alpha iron.

The results are summarized by the series of curves in Fig. 2. Each curve (2 to 9) is the apparent limit of the martensitic field for the condition of heat treatment and strain to which the index refers.

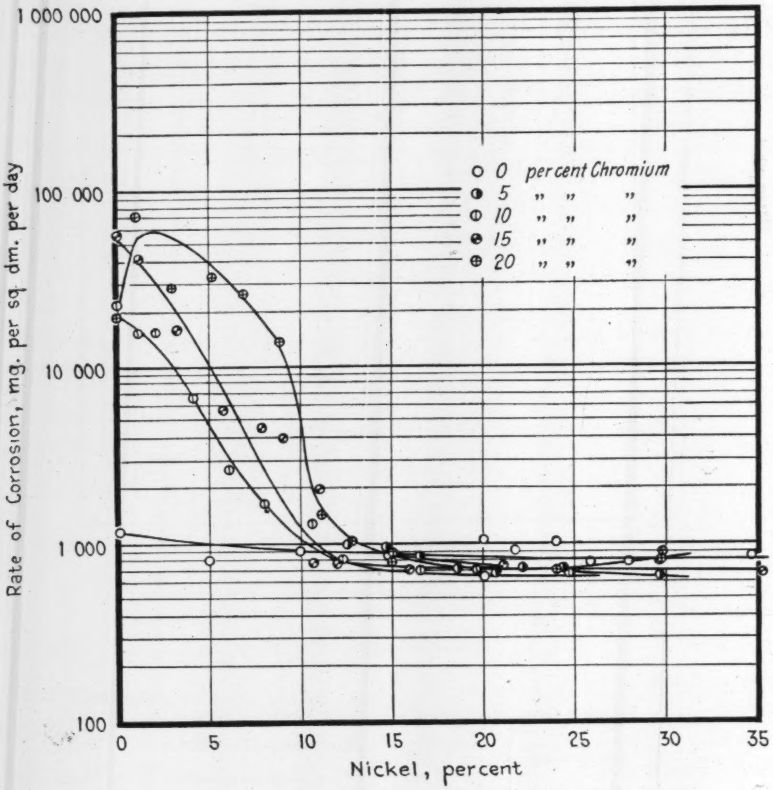

FIG. 3.—Corrosion Rates of Iron-Chromium-Nickel Alloys in 5-per-cent Sulfuric Acid.

For example, the alloy 18 per cent chromium and 8 per cent nickel was wholly austenitic only when quenched from 800° C. or above; it precipitated alpha iron when heated at 700° C., or when strained following quenching from any of these temperatures.

By examining these curves closely it will be seen that the lower the temperature of heat treatment the higher the nickel or the chromium contents which respond, and then when strained in tension to fracture the series repeats itself but is shifted to even higher alloy contents. At temperatures below about 600° C. the changes occur only very slowly.

The important point is not the precise location of any of these curves, but the fact that they are restricted to a definitely limited range in the austenitic field. The limits of this range of marginal, unstable austenitic alloys are the curves 3 and 4, in Fig. 1. (Curve 4, Fig. 1, has been drawn coincident with curve 8, Fig. 2.) To the right of curve 4 (higher nickel or chromium), the alloys appear to be permanently austenitic; to the left of curve 4 an alpha-iron phase may form, this action becoming more intense the closer curve 3 is approached. Since the commercially important alloy 18 per cent chromium, 8 per cent nickel lies within this range, it becomes desirable to see what changes in useful properties this instability may bring about.

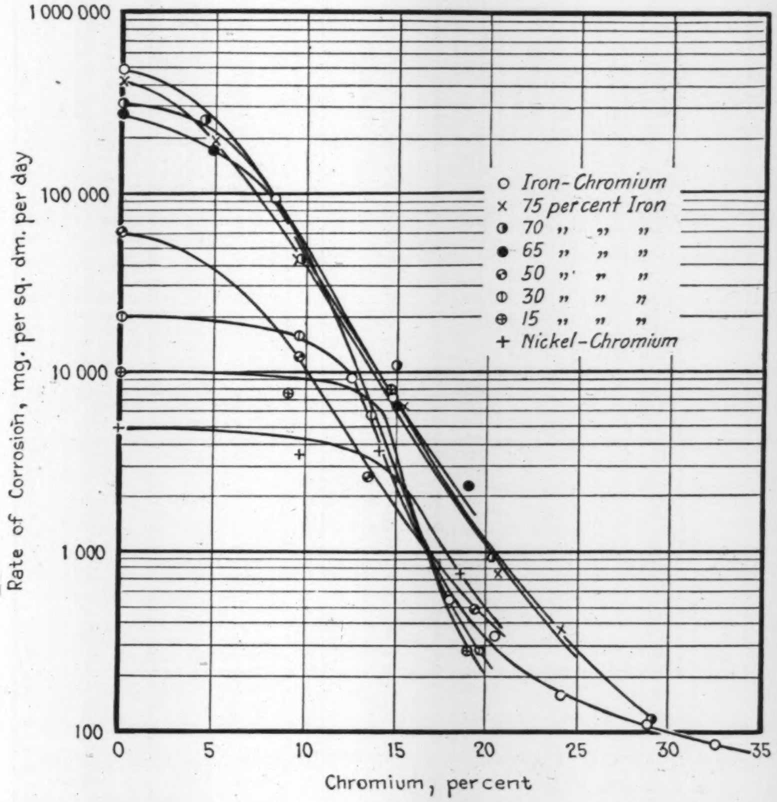

FIG. 4.—Corrosion Rates of Iron-Chromium-Nickel Alloys in 5-per-cent Nitric Acid.

CORROSION RESISTANCE

The usefulness of the iron-chromium-nickel alloys is inseparably associated with their corrosion-resisting properties, and any discussion of physical qualities cannot well neglect their chemical characteristics. It is hard to deal briefly yet accurately with questions of corrosion, as the circumstances in concrete cases are usually very complex. However, as a guide to the major consequences of change in chromium and nickel content, it is perhaps sufficient for the present to consider the action of two different classes of corrosive agents, namely, reducing acids and oxidizing acids. It is convenient for this

TABLE III.—TENSILE DATA.

Alloy	Chemical Analysis					Heat Treatment				Proportional Limit, lb. per sq. in.	Yield Point (0.5 per cent deformation), lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value, ft-lb.
	Nickel, per cent	Chromium, per cent	Carbon, per cent	Silicon, per cent	Manganese, per cent	Temperature, deg. Cent.	Hours	Cooled	Number of Tests						
No. 37	9.79	17.87	0.06	0.20	0.23	600	½	Water quench	2	23 000	43 000	96 300	54	69	116
						700	"	" "	2	25 200	43 000	94 900	52	68	119
						800	"	" "	2	31 000	46 400	95 900	52	70	119
						900	"	" "	2	29 500	46 000	95 700	53	73	119
						1000	"	" "	2	26 500	43 000	89 700	58	76	119
						1100	"	" "	2	22 000	38 000	84 800	64	77	119
						1200	"	" "	2	23 500	37 800	83 000	67	78	116
No. 38	9.38	17.10	0.10	0.56	0.47	600	½	Water quench	2	23 500	34 200	88 000	68	72	109
						700	"	" "	2	20 800	34 000	93 900	60	69	114
						800	"	" "	2	25 500	34 500	94 000	58	65	114
						900	"	" "	2	22 800	35 300	93 400	60	66	114
						1000	"	" "	2	23 500	34 000	90 400	64	73	110
						1100	"	" "	2	22 000	33 200	90 700	65	74	108
						1200	"	" "	2	23 500	32 000	87 100	67	75	102
No. 39	8.06	17.65	0.14	0.34	0.17	600	1	Water quench	2	17 500	43 200	117 500	32	25	117
						700	2	" "	1	24 000	45 000	138 800	50	52	92
						700	24	" "	1	23 000	41 000	137 500	36	53	53
						800	½	" "	1	25 000	46 000	135 200	40	35	99
						1000	½	" "	1	29 000	42 500	129 700	31	23	96
						1200	¼	" "	2	22 500	31 500	113 200	54	36	103
No. 40	14.72	18.21	0.06	1.26	0.53	600	½	Water quench	2	27 500	40 000	87 000	60	66	116
						700	"	" "	2	25 000	41 500	86 100	54	66	116
						800	"	" "	2	27 000	41 500	85 600	53	64	112
						900	"	" "	2	27 000	41 500	85 900	54	66	116
						1000	"	" "	2	27 000	40 000	83 500	58	77	119
						1100	"	" "	2	20 500	34 500	79 000	65	77	103
						1200	"	" "	2	21 500	34 000	76 000	69	76	101
No. 41	15.09	18.07	0.10	0.06	0.44	600	½	Water quench	2	31 000	43 500	89 500	52	67	117
						700	"	" "	2	29 000	44 000	89 600	49	70	119
						800	"	" "	2	29 000	42 500	89 100	47	66	118
						900	"	" "	2	28 000	44 000	88 800	47	60	116
						1000	"	" "	2	25 500	43 200	87 100	51	72	118
						1100	"	" "	2	21 800	34 800	79 700	55	77	105
						1200	"	" "	2	23 500	35 000	78 300	58	78	106
No. 42	15.46	15.04	0.23	0.19	0.81	600	1	Water quench	2	24 000	46 500	94 300	50	57	83
						700	2	" "	1	18 000	43 500	93 600	51	65	91
						700	24	" "	1	20 000	43 000	91 300	49	64	86
						800	½	" "	1	21 500	46 000	91 600	51	61	82
						1000	½	" "	1	26 500	45 000	92 900	51	68	101
						1200	¼	" "	1	20 000	36 500	86 500	67	74	106

purpose to reproduce two diagrams from an earlier paper.[1] Figure 3 shows the effect of nickel and chromium contents on the solution rate in a typical reducing acid, air-saturated dilute sulfuric acid. It appears that in order to realize the highest resistance to this type of corrosive agent, a nickel content in excess of about 13 per cent is necessary, this percentage being the same for chromium contents at least up to 20 per cent. With lower nickel contents, the solution rate increases very rapidly. Figure 4 shows the effect of nickel and chromium content on the solution rate in a typical oxidizing agent, dilute nitric acid. In this case, the resistance to attack depends almost entirely upon chromium content, at least down to iron contents of about 60 per cent.

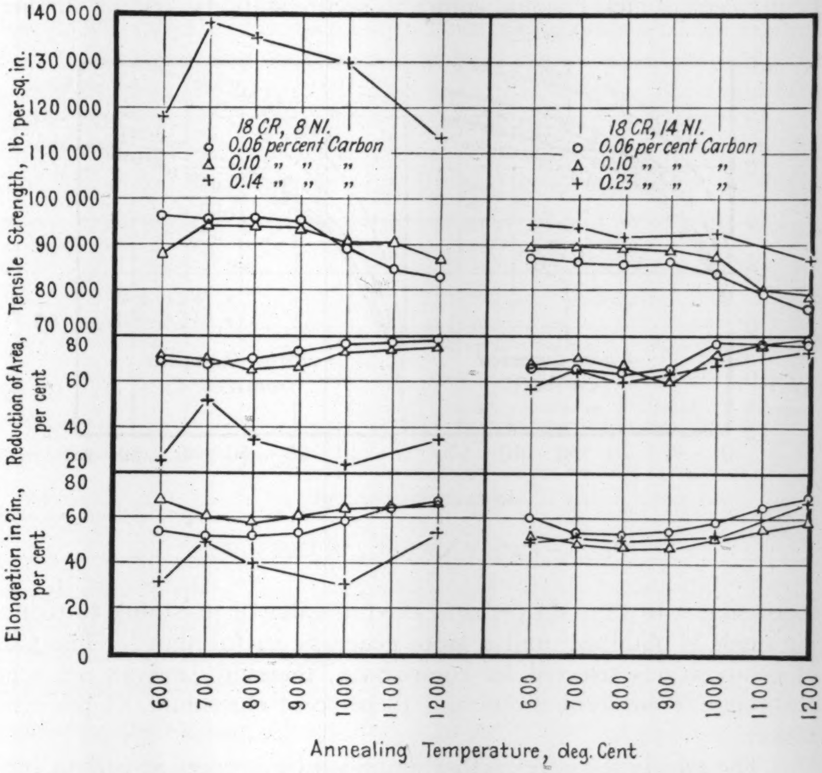

FIG. 5.—Tensile Properties of 18 per cent Chromium, 8 per cent Nickel and 18 per cent Chromium, 14 per cent Nickel.

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[1] N. B. Pilling and D. E. Ackerman, *Proceedings*, Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 248 (1929).

COMPARISON OF TYPICAL MARGINAL AND STABLE AUSTENITIC ALLOYS

We can now revert to the question of stable *versus* unstable alloys. The marginal range can only be escaped by increasing either nickel or chromium content; it is accomplished most effectively by an increase in nickel. From Fig. 1 it appears that an increase to 12 per cent of nickel should suffice to secure stability, but by further increasing it to 13 or 14 per cent the full value of resistance to reducing acids is obtained, and a more generally useful alloy. The pair of compositions selected for comparison, therefore, was 18 per cent chromium, 8 per cent nickel and 18 per cent chromium, 14 per cent nickel.

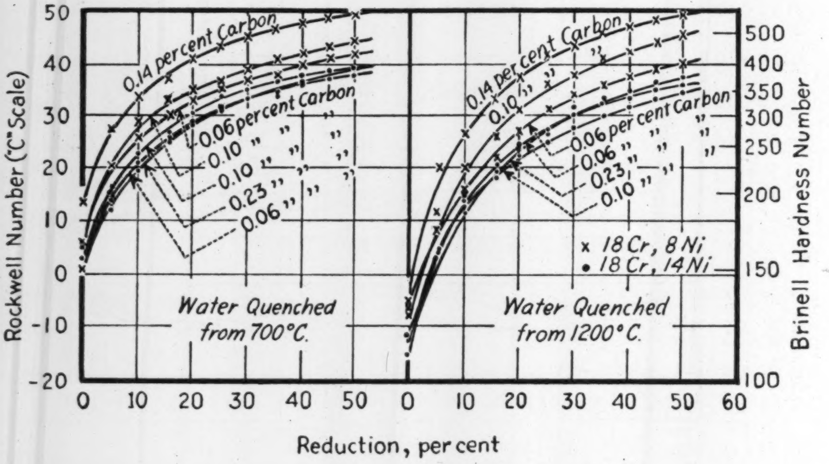

FIG. 6.—Rate of Hardening by Cold Rolling.

The two types were further amplified by a range of carbon contents, about as shown:

	18 PER CENT CHROMIUM, 8 PER CENT NICKEL	18 PER CENT CHROMIUM, 14 PER CENT NICKEL
Carbon, per cent	0.06	0.06
" "	0.10	0.10
" "	0.14	0.23

These alloys were available from fairly large melts of one-half-ton size or greater, and all were rolled to sheet and rod on commercial mills.

Tensile and Impact Properties:

The hot-rolled rods were heated to a succession of temperatures between 600 and 1200° C., the heating being terminated by quenching in cold water. Full details of heat treatment and test results are given in Table III; from this a selection of data has been plotted for comparison in Fig. 5.

As a group, the high-nickel alloys are consistently softer than the low-nickel alloys. The decrease in strength accompanied by marked increase in elongation which occurs at heat treatments above 1000° C. seems to be characteristic of most austenitic alloys. The important distinction between them, however, is the difference in response to increase in carbon content and this is clearly shown in the figure. The low-nickel alloy hardens rapidly and loses ductility; the high-nickel alloy hardens only moderately and retains its ductility. The practical significance of this will be discussed later. The impact strength of the highest-carbon content alloys only was affected by heating at 600 to 800° C.

TABLE IV.—INCREASE IN HARDNESS PRODUCED BY REDUCTION IN THICKNESS OF 20 PER CENT.

Type	Carbon, per cent	Brinell Hardness			
		Water Quenched from 1200° C.		Water Quenched from 700°. C	
		Initial	Increase	Initial	Increase
18 per cent chromium, 8 per cent nickel......	0.06	130	148	160	180
	0.10	123	187	148	192
	0.14	128	243	191	232
18 per cent chromium, 14 per cent nickel.....	0.06	109	141	148	144
	0.10	109	141	160	140
	0.23	116	140	150	134

Cold Working Properties:

Another property of importance is the rate of hardening by cold working. A quantitative comparison was made by cold rolling small plates about ⅛ in. thick initially, and following the hardness change during rolling. The hardness is conveniently measured on the Rockwell instrument, yet owing to the compression of the higher ranges of this scale it is more instructive to translate such measurements to the Brinell scale for comparisons. The relation between the two developed by Petrenko[1] is sufficiently close for this purpose.

Two comparisons of work-hardening rate are given in Fig. 6, corresponding to two different initial conditions: (1) water quenched from 1200° C. and (2) water quenched from 700° C.

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[1] *Technologic Paper No. 334*, U. S. Bureau of Standards.

The general situation is parallel to that developed by the tension tests. The low-nickel alloy hardens far more rapidly with increase in carbon content than the high-nickel alloy. This is demonstrated in Table IV, showing the rise in hardness produced by a reduction in thickness of 20 per cent. The necessity for low-hardening rates in certain types of shaping and fabricating operations is evident.

Annealing:

The softening characteristics of 18 per cent chromium, 14 per cent nickel containing 0.07 per cent carbon and cold-rolled 40 per cent are shown in Fig. 7. The first appreciable softening for an annealing period of 30 minutes occurs at about 700° C., and from 800 to 1100° C. the hardness falls continuously with rising annealing temperature. As heating at the highest of these temperatures develops the highest degree of ductility, annealing temperatures in excess of 1100° C. are commonly used, followed by quenching to prevent the precipitation occurring at lower temperatures. A disadvantage of high-temperature heat treatment is that the grain size becomes very coarse and a rough surface texture develops if the metal is stretched. For this and other reasons it is desirable to soften cold-worked articles at temperatures below that of excessive grain growth, as from 850 to 1000° C. With the higher nickel type of alloy this may safely be done without fear of the disturbing alpha precipitation, and the practical result is that alloys of even moderately high carbon content may be softened adequately and yet retain a very small grain size, a combination of qualities well

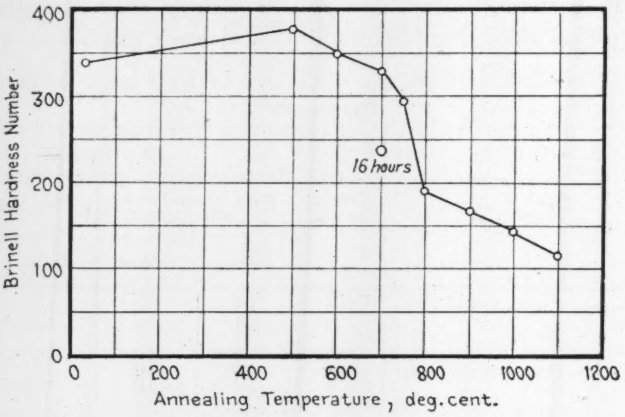

FIG. 7.—Softening of Cold-Rolled 18 per cent Chromium, 14 per cent Nickel.

suited for deep-drawing purposes. Wholly satisfactory cold presswork has been done upon stock annealed at 900° C.

Carbide Embrittlement:

The chromium-nickel austenitic alloys are subject to a curious yet important susceptibility to intercrystalline corrosion after exposure to temperatures in the precipitation range. This may be induced by a number of corrosive media. No discussion in detail will be given but a few tests will be cited which tend to show that although the marginal and stable groups are both to a certain extent susceptible, it is possible to demonstrate certain rather consistent differences. Table V shows the result of three series of tests upon a number of individual alloys of the two types. These had all been heated at 650-725° C. for several hours, and the duration of test was variously from 20 to 170 hours. When boiling acid ferric sulfate was the stimulant, only those 8-per-cent nickel alloys containing over 0.12 per cent carbon failed, and none of the 14-per-cent nickel group failed. In boiling acid copper sulfate solution, both groups responded rather similarly, carbon contents of 0.09 per cent or less not failing. When strained by cold-rolling 5 per cent, after first heating at 650° C., every specimen in the 18 per cent chromium, 8 per cent nickel group failed in acid copper sulfate, even with carbon contents as low as 0.05 per cent, while those 14-per-cent nickel alloys containing 0.07 per cent carbon or less were completely resistant. This behavior might be interpreted as indicating that the precipitation of alpha iron and of carbides may occur independently, and that both may serve to stimulate this embrittlement.

TABLE V.—CORROSION-EMBRITTLEMENT TESTS.

Type	Alloy	Chemical Composition					10 per cent Ferric Sulfate, 0.1 per cent H_2SO_4	10 per cent Copper Sulfate, 10 per cent H_2SO_4	
		Nickel, per cent	Chromium, per cent	Carbon, per cent	Manganese, per cent	Silicon, per cent		As Heat Treated	Heat Treated and 5 per cent Cold Reduction
Marginal Austenitic	No. 22	8.91	17.14	0.05	0.51	0.31	No action	No action	Failed
	No. 23	9.28	18.50	0.07	0.42	0.19	No action	No action	Failed
	No. 24	10.33	15.57	0.12	0.41	0.38	Failed	Failed	Failed
	No. 25	8.06	17.65	0.14	0.17	0.34	No action	Failed	Failed
	No. 26	8.90	17.86	0.16	0.43	0.62	Failed	Failed	Failed
	No. 27	7.00	19.82	0.16	0.50	0.59	No action	......	Failed
	No. 28	7.53	17.82	0.17	0.26	0.40	Failed	......	Failed
Stable Austenitic	No. 29	15.11	19.85	0.06	0.55	1.42	No action	No action	No action
	No. 30	14.45	19.77	0.07	0.52	1.30	No action	No action	No action
	No. 31	14.12	19.29	0.09	0.52	1.28	No action	No action	Failed
	No. 32	15.09	18.07	0.10	0.44	0.06	No action	Failed	Failed
	No. 33	14.54	18.65	0.12	0.37	1.18	No action	No action	Failed
	No. 34	14.38	17.61	0.13	0.41	1.07	No action	Failed	Failed
	No. 35	15.46	15.04	0.23	0.81	0.19	No action	Failed	Failed
	No. 36	15.15	13.62	0.25	0.65	0.13	No action	Failed	Failed

Welded test specimens of 8 and 14-per-cent nickel alloys, containing 0.14 and 0.23 per cent carbon, respectively, were subjected to prolonged corrosion in sulfuric acid solution at room temperature. The former developed severe intercrystalline corrosion along the flanks of the weld while the latter suffered none. Evidently the significance of such artificial tests as these requires careful consideration.

GENERAL DISCUSSION

It has been shown that some of the austenitic chromium-nickel steels have the power of precipitating alpha iron under certain conditions of heat treatment and strain, and the composition limits of this range have been approximately placed. Some of the detailed consequences of this instability have been traced out, a point of special interest being that carbide precipitation is attended by more serious results when it is accompanied by the formation of a ferritic phase.

The completely stable type of alloy has at least two useful advantages:

1. It insures a completely austenitic structure, which is essential in some electrical and high-temperature services.
2. It has a greater tolerance for higher carbon contents.

This latter gives a desirable latitude in composition for those manifold applications where appearance and fabricability are dominating considerations, rather than the ability to withstand the severest exactions of temperature and corrosion. It may best be achieved by a modest increase in nickel content, the cost of which can largely be written off by the more inexpensive grades of ferro-chromium which it becomes possible to use. This is a matter which should appeal equally to the steel maker and the user, and the economics involved deserve careful consideration.

DISCUSSION

MR. J. A. MATHEWS[1] (*presented in written form*).—The paper by Mr. Pilling contains some interesting data in regard to certain inherent properties of austenitic chromium-nickel alloys. It attempts to refine the structural diagram of Strauss in regard to these steels and particularly to give a more exact line indicating the boundary between truly austenitic steels and the austenitic-martensitic type. In the writer's judgment, this line cannot be exactly defined without taking into consideration both the carbon and the silicon content, as well as that of the chromium and nickel.

The paper does not add much to our knowledge of the 18 per cent chromium, 8 per cent nickel steel in addition to that which has frequently been pointed out by Benno Strauss and by the manufacturers of this type of steel, who have used every effort in their power to prevent misapplications of this extremely useful product. Finding fault with the so-called 18 per cent chromium, 8 per cent nickel steel seems to have become a popular sport and at the May meeting of the American Iron and Steel Institute, Mr. F. M. Beckett presented a paper in which he had a remedy for all the defects of the 18 per cent chromium, 8 per cent nickel steel by replacing the nickel altogether with manganese and Mr. Pilling would do so by increasing the nickel content. It will be noted that about 8 per cent of nickel is the mean between the recommendations of these two metallurgists. Like every important alloy it has its proper field and it is not offered as a cure-all for every corrosion problem which may arise.

The types of steels containing the higher nickel content, to which Mr. Pilling refers, have long been available. In general, they have not been as widely used as the 18 per cent chromium, 8 per cent nickel steel, first, because of their greater cost, second, because they are not advantageous under so many conditions, particularly in the presence of sulfur compounds resulting from highly sulfurous fuels; when the nickel is increased for use in this application it seems to be indicated that the chromium be proportionately increased—still further raising the cost. Such steels include the 22 per cent nickel, 12 per cent chromium type.

There have also been available for a long time steels in which the nickel is higher than the chromium, as for example the 8 per cent chromium, 18 per cent nickel and the 17 per cent chromium, 25 per cent nickel steels. All of these steels may be considered "special purpose" steels and have not anywhere near the wide applicability of the 18 per cent chromium, 8 per cent nickel type. Benno Strauss and others have pointed out that with this type of steel the embrittlement danger is very much minimized or entirely removed when the carbon is kept very low—for example below 0.07 per cent—or when the steel is subjected to the Strauss treatment which consists of quenching in water from about 2000° F. which results in the formation of homogeneous austenitic steel free from carbides. When such steel is intended for applications at somewhat elevated temperatures, between 1000 and 1500° F., resort to the low carbon is desirable. For use at atmospheric temperatures the higher carbons are permissible, providing the steel receives a high-temperature quench, known as the Strauss treatment.

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[1] Vice-President and Metallurgist, Crucible Steel Co. of America, New York City.

In Table V of Mr. Pilling's paper, the action of certain reagents is pointed out. These tests were made after the steel had been put into its worst possible condition by long annealing within the embrittlement range. Even under these conditions there is no failure with the extremely low-carbon alloys, Nos. 22 and 23, except after cold working. If the properties of the 18 per cent chromium, 8 per cent nickel steel and the conditions of use are understood trouble can be avoided either by heat treatment or by proper selection of analysis, or both. Furthermore, the particular conditions chosen by the author to produce embrittlement are not usually present.

In the past, the use of 18 per cent chromium, 8 per cent nickel steel under ideal conditions as to both use and treatment has not always been attained, nevertheless the failures and disappointments in the use of this steel have been relatively few. When satisfactory results cannot be obtained from this material, either by selection of suitable analysis or by heat treatment of the finished product after fabrication, then we must look to the "special purpose" compositions referred to above and suggested in Mr. Pilling's paper and which have been used successfully in a great variety of applications. For a great many corrosion-resistant applications chromium additions to iron are all that is needed. When nickel is used to produce certain physical properties we may have to sacrifice somewhat in corrosion resistance because of its use. In a more restricted field a high nickel content seems to provide necessary corrosion resistance but I cannot, at the moment, think of any place where the resistance is not further improved by the simultaneous presence of a substantial amount of chromium.

Those who are interested in the subject of carbide precipitation are referred to a paper by B. Strauss, H. Schottky and J. Hinnueber, in the January, 1930, number of *Zeitschrift für anorganische und allgemeine Chemie.*

MR. W. M. MITCHELL[1] (*presented in written form*).—Mr. Pilling's paper is a very important and timely contribution to the literature of the stainless alloys. While the commercial development of this interesting group of metals has been generally a series of brilliant successes, dark spots have been visible in the procession—and it is well for us to realize that there are limitations to these alloys which must be recognized and allowed for.

Some six or seven years ago, the advent of the first stainless iron was welcomed with much acclaim, only to be followed by the discovery that its corrosion resistance was not in accordance with expectations and that it was distinctly a hardenable alloy—also not in accordance with expectations. This was followed by the high-chromium, low-carbon stainless iron of the Armstrong patents. This proved definitely superior in corrosion resistance and has achieved some notable successes: namely, in the manufacture of nitric acid. But its mechanical qualities are not all that are desired and it is somewhat lacking in workability, particularly in regard to forming, deep drawing, etc. Owing to its limitations of strength and workability, a better product was sought. This was supplied by the chromium-nickel stainless alloys of the 18 per cent chromium, 8 per cent nickel type. These were rightly heralded as superior in corrosion resistance and workability to the straight chromium alloys.

While the 18 per cent chromium, 8 per cent nickel alloy is certainly the best of the analyses for general purposes so far commercially produced, actual service and better acquaintance with its working qualities have disclosed certain limitations which Mr. Pilling has noted in his paper. These are the tendency to harden on cold working, the precipitation of carbides and the formation of alpha iron when heated to moderate temperature ranges; the latter frequently resulting in failures of equipment fabricated by welding when subjected to severe chemical attack.

The precipitation of carbides and formation of alpha iron may easily be remedied by the well-known high-temperature treatment. The importance of this, and its necessity, are facts which no metallurgist can deny, but in many instances heat treatment after fabrication is impracticable because of the size or shape of the piece. This difficulty may be overcome by the use of an 18 per cent chromium,

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[1] Assistant Sales Manager, Development Division, Republic Steel Corp., Youngstown, Ohio.

8 per cent nickel alloy, with extremely low carbon content. Carbide precipitation is thus so greatly reduced that it may be virtually disregarded.

The tendency to work-harden is not so easily dealt with. Mr. Pilling has recommended the addition of some 6 per cent of nickel to the 18 per cent chromium, 8 per cent nickel combination, as a means of transferring the alloy from what he calls the "marginal austenitic" type to the "permanent austenitic" type. It will be interesting to observe if steel makers follow this suggestion, and if the addition of this considerable proportion of nickel sufficiently reduces work hardening tendency to justify its cost. Possibly, an alloy with a smaller increase in nickel, such as Brown-Bailey's "Anka," may prove sufficiently suitable for general application. This appears to be initially softer than the 18 per cent chromium, 8 per cent nickel alloy and less subject to work hardening. Perhaps, also the substitution of some other element for nickel in part, as for instance, manganese which has been advocated by Becket, may ensure the necessary austenitic stability—and further research in this direction is most desirable.

In any event, the future must witness still greater application and use of stainless alloys, whether of the present 18 per cent chromium, 8 per cent nickel type or some other type still to be developed. Mr. Pilling is to be thanked for having cleared the air on certain subjects, and for suggesting a remedy for some of our difficulties.

MR. JEROME STRAUSS.[1]—I have only appreciation to express for the experimental work which Mr. Pilling has recorded in this paper. There is, however, one statement in the general discussion that I think deserves some revision. The author has remarked that his purposes are accomplished by a moderate increase in nickel content, the cost of which can largely be written off by the more inexpensive grades of ferro-chromium which it becomes possible to use. I think it will be found that the cost of the nickel content increase is approximately forty dollars per ton, while the saving due to the higher carbon ferro-chromium would amount to somewhere between five and ten dollars a ton.

MR. HOWARD SCOTT.[2]—Just one point I want to make about the effect of manganese and carbon, namely, that manganese and carbon have the effect of displacing the unstable range. The effect of manganese, I found in another group of iron-base alloys to be about two and a half times that of nickel, and carbon to be something like eighteen times as effective as nickel in lowering the gamma to alpha transformation. In other words, 0.4 per cent of manganese is equivalent to 1 per cent of nickel. I noticed in one of the tables that the manganese range is from 0.2 to 1 per cent which is equivalent to a difference in nickel content of 2 per cent. The author has not mentioned these relations which are of considerable importance in determining the stable composition range of the iron-chromium-nickel alloys.

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[1] Chief Research Engineer, Vanadium Corporation of America, Bridgeville, Pa.

[2] Research Engineer, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

MR. P. H. BRACE.[1]—I want to ask Mr. Pilling whether there is at this time any alloy of this type which will stand prolonged exposure to temperatures that range between 400 and 600° C. without developing embrittlement?

Mr. Pilling mentioned welded specimens and the occurrence of inter-crystalline corrosion along the flanks of the weld. Does that mean that the corrosion occurred in portions of the material which had been actually fused and perhaps alloyed with deposited weld metal or was it outside the zone of fusion? I think a lot of difficulty has developed and a lot of discussion arisen with respect to 18 per cent chromium, 8 per cent nickel steel due to the fact that the steel makers of this country did not know their alloy well enough. I happen to know of one case where, apparently with the supplier's knowledge of the service conditions, a user was committed to the application of nearly a million dollars' worth of this alloy under conditions which involved exposure to temperatures in the range I mentioned over periods which will run into years in the aggregate and with mild corrosion agents present. Now, in that particular application, apparently the standard 18 per cent chromium, 8 per cent nickel alloy should not be used and in line with my first question I should like to know if there is any material now available in the American market which will withstand that service?

MR. N. B. PILLING.[2]—Regarding Mr. Strauss' question as to whether there is really any saving in cost by using cheaper ferro-chromium to pay for the increase in nickel content, I cannot follow his figures exactly, but if it is necessary to use the highest grade of ferro-chromium containing 0.06 per cent carbon maximum in order to get the grade of steel wanted, the price differential between that and 0.5-per-cent carbon ferro-chromium, which would be practicable according to our thought, is of the order of six cents a pound. With a chromium content of 18 per cent in the alloy the saving amounts to about $1\frac{1}{4}$ cents which pays for about 4 per cent of nickel, and that is enough. It was not our intention to make any arbitrary selection of a new alloy to be regarded as the best example of the new definition; the 14-per-cent nickel content was taken as a fair example to demonstrate its characteristics. It is entirely possible that maintaining the chromium content at 18 per cent and increasing the nickel content to 12 per cent will accomplish a great deal, but there are other proportions which are better suited for particular conditions of service. The curve shown in Fig. 1 of the paper marking off the limits of the stable field is a guide to a number of proportions of chromium to nickel, all of which avoid the disadvantage of hard fabricability.

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[1] Engineer, Research Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] Metallurgist, The International Nickel Co., Bayonne Laboratory, Bayonne, N. J.

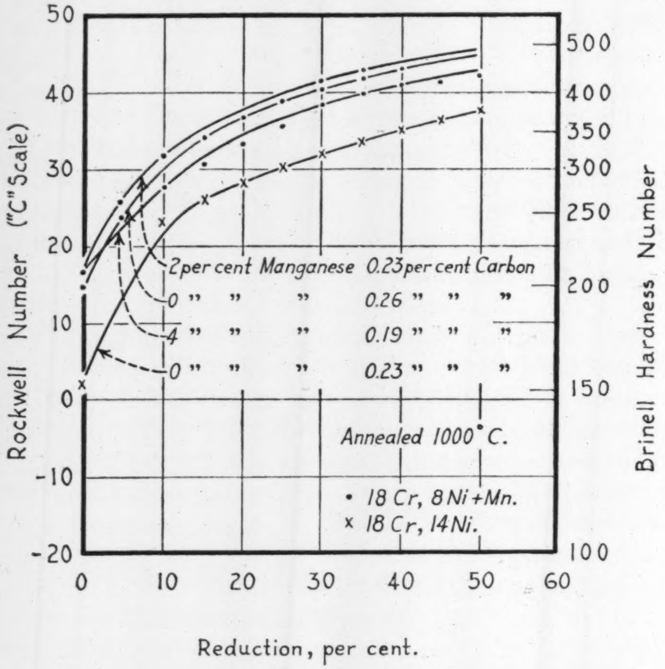

Fig. 1.—Effect of Manganese on 18 per cent Chromium, 8 per cent Nickel Alloy.

Regarding Mr. Mathews' discussion, I am in sympathy with much of what he says. There is no intention to discredit any alloy. The paper simply shows the advantages of some of the higher nickel content alloys mentioned which do not seem to have been fully appreciated before.

Mr. Mitchell referred to Brown-Bailey's "Anka" steel as perhaps meeting the new definition. Unless it has been changed, I recall that "Anka" contains about 15 per cent of chromium and 10 per cent of nickel. That is a step in the right direction, but it does not go quite far enough; it still falls within the debatable ground, and a little more nickel, maintaining the chromium content as high as 18 per cent, would seem desirable.

The question of a manganese content to accomplish the effect of a higher nickel content, but more cheaply, is brought up by Mr. Mitchell. It happens that we have a little information bearing directly on that point. The accompanying Fig. 1 shows the effect of a content of manganese added to 18 per cent chromium, 8 per cent nickel and shows whether or not the increase in manganese content accomplishes the effect of an increase in nickel content in eliminating the excessive hardening of cold working. In order to demonstrate this adequately, the carbon contents have been selected at 0.2 per cent: that is, high enough to give a well-marked effect with 18 per cent chromium, 8 per cent nickel alloy, and yet no effect with 18 per cent chromium and 14 per cent nickel. The four curves shown include 18 per cent chromium, 14 per cent nickel, and 18 per cent chromium, 8 per cent nickel, with 0, 2 and 4 per cent manganese, respectively. These manganese contents are equivalent, according to Mr. Scott's figures, to 5 per cent and 10 per cent nickel, respectively. It will be seen that the rate of hardening is unaffected by these manganese contents, and the action of nickel is unique.

The corrosion of the welded test specimen about which Mr. Brace inquires occurred in the plate metal outside of the zone of fusion. His other question touches a complicated but most important point and it is evidently not possible to give a simple answer to it yet.

THE UNBALANCED ALTERNATING CURRENT BRIDGE FOR MAGNETIC ANALYSIS

BY W. B. KOUWENHOVEN[1] AND A. C. SELETZKY[2]

SYNOPSIS

An alternating current bridge has been developed which tests ferrous materials independently of their cross-sections. Two coils and two resistances, one of which is variable, constitute the four arms of the bridge. A standard specimen is placed in one coil and the unknown specimen in the other coil and the galvanometer deflection is reduced to zero by varying the resistance.

An alternating current galvanometer with a variable field phase displacement is used as a detector. By varying the phase of the galvanometer field the bridge may be balanced on any component of the exciting current flowing through the two coils. When the phase of the field has a displacement angle such that the bridge balances on either the loss or magnetizing component of the exciting current, specimens may be compared with a standard, provided they have the same length and cross-section; at a certain value of phase displacement of the galvanometer field, the bridge reading does not depend on the ratio of the cross-sections of the specimens being compared, but only on the character of the material, the lengths of the specimens being equal.

Specimens have been successfully tested, the cross-sections of which varied from one-quarter to twice that of the standard. Wide variations in voltage and frequency have no effect on the readings. The bridge has been studied analytically and the theory of operation is presented. The practical application of the bridge in this investigation was in the testing of pocket knife blades; it may be readily adapted, however, to the testing of many products made of ferrous materials.

INTRODUCTION

The segregation of ferrous materials by magnetic analysis using alternating current has been studied by deForest,[3] Kouwenhoven,[4] Spooner,[5] Styri[6] and Kouwenhoven and Tebo.[7] An essential feature in their work was the use of an alternating current galvanometer, the phase of whose field excitation could be varied. This renders the galvanometer sensitive to the component of the current in the moving coil, which is in the same phase as the galvanometer field. Generally, separation among specimens has been effected by measuring quantities, which are proportional either to the magnetization or the loss, or both, in the specimen.

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[1] Associate Professor of Electrical Engineering, Johns Hopkins University, Baltimore, Md.

[2] Graduate Student in Electrical Engineering, Johns Hopkins University, Baltimore, Md.

[3] A. V. deForest, "A New Method of Magnetic Inspection," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 611 (1923).

[4] W. B. Kouwenhoven, "Magnetic Tests of A.S.T.M. Drills," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 635 (1924).

[5] Thomas Spooner, "The Magnetic Analysis of High-Speed Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 116 (1926).

[6] Haakon Styri, "Testing of Ball Bearing Races by Electric and Magnetic Methods," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 148 (1926).

[7] W. B. Kouwenhoven and J. D. Tebo, "The Incremental Permeability Method for Magnetic Analysis of High-Speed Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 356 (1928).

Inasmuch as the magnetization or flux and the loss are different functions of the cross-section, the length being considered constant, the specimens being compared must be of equal size. This at once limits the methods developed so far to materials or products which are of the same dimensions, a not altogether desirable restriction.

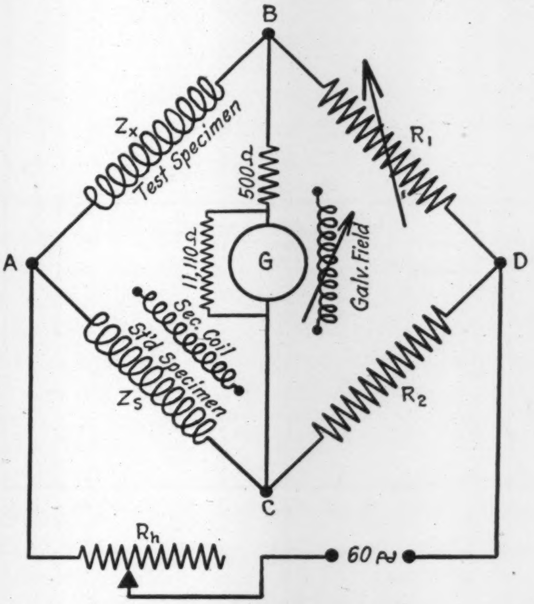

FIG. 1.—Diagram of Bridge Circuit.

This paper describes a method of magnetic analysis which is independent of the cross-sections of the specimens within rather wide limits. It is based upon the comparison of a standard and an unknown specimen in an alternating current bridge in which the phase of the galvanometer field is adjusted to a component that is independent of the cross-sectional areas of the samples.

THE BRIDGE

The bridge used is shown in Fig. 1. Z_x and Z_s are two coils exactly alike of 400 turns each, 10 in. long, and having an ohmic resistance of 1.22 ohms. These coils were built to accommodate steel specimens 10.2 in. long, 1.9 in. wide and from 0.061 to 0.135 in. in thickness. The fixed resistance R_2 had a value of 0.84 ohms, and R_1 was a variable slide wire resistance with 0.002888 ohms per scale division. The galvanometer used was a Leeds and Northrup pointer type alternating current galvanometer, with a sensitivity of one microampere per mm. deflection, and a resistance of 250 ohms. The galvanometer coil was shunted with a resistance of 11,110 ohms for damping. An additional series resistance of 500 ohms was placed in the galvanometer circuit to limit the current through the instrument. The phase of the excitation of the galvanometer field was varied by means of a phase shifting transformer.

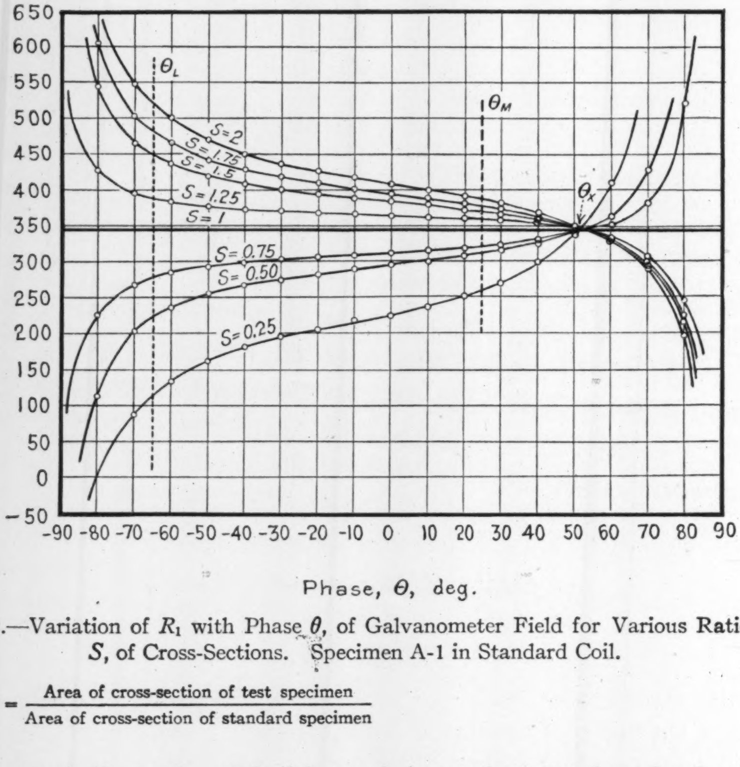

FIG. 2.—Variation of R_1 with Phase θ, of Galvanometer Field for Various Ratios, S, of Cross-Sections. Specimen A-1 in Standard Coil.

$$S = \frac{\text{Area of cross-section of test specimen}}{\text{Area of cross-section of standard specimen}}$$

All of the measurements reported in this paper were made at 60 cycles. A number of tests were also made at other frequencies varying from 25 to 140 cycles. The resistance R_h was used to control the current through the bridge. The circuit was so arranged that the currents I_x and I_s passing through the Z_x and Z_s coils, respectively, could be readily measured.

The coil, Z_s, containing the standard specimen was provided with a secondary winding for use in adjusting the phase relation of the galvanometer field. The phase of the galvanometer field at which the deflection produced by the voltage induced in this secondary coil was a maximum, was called θ_l and the position 90 deg. away θ_m. When the galvanometer was reconnected to the bridge the values of R_1 for balance at field position θ_l and θ_m were not only a function of the magnetic qualities of the samples being compared in the two coils, but also of their cross-sectional areas. However, it was found that at a certain position of the galvanometer field the bridge setting was independent of the cross-sections and only dependent upon the magnetic properties of the material; this point we have designated as θ_x.

THEORY

In order to investigate the behavior of the bridge at different settings of the galvanometer field for specimens differing in cross-section, sheet material was used. Six groups of four samples each were available, all of the samples of each group having the same chemical composition, the same cross-section, and the same heat treatment. Some of the specimens were cut lengthwise into halves and quarters, thus making it possible to compare specimens having different ratios of cross-section.

One full size specimen was kept in the standard coil, Z_s, and various combinations of whole and fractional specimens were placed in the test coil, Z_x, and compared against the standard. With a given ratio of cross-section, the phase of the galvanometer field, θ, was varied in increments of 10 deg., and the bridge balanced by adjusting R_1. The results for one group of samples are shown in Fig. 2. The ratio of the area of cross-section of the test specimen to that of the standard is denoted by S. It will be noticed that when S is unity the bridge is perfectly balanced and the value of R_1 is constant for all displacements of the galvanometer field. This is what would be expected because the cross-sections and the magnetic qualities of the two specimens are alike and therefore the coil impedances are equal.

The important and peculiar features of all these curves is that they intersect at one point, θ_x, which shows quite definitely that the value of R_1 for balance, when the galvanometer field phase is at this point, is the same for all values of S, from $\frac{1}{4}$ to 2. The space within the coils did not permit the insertion of more than two whole specimens.

Similar sets of curves were obtained with the other groups of specimens. The values of θ_x, however, differed as did also R_1; by virtue of these differences it was possible to obtain magnetic separation independent of cross-section over the range studied.

All of the curves in Fig. 2 may be expressed as a function of the tangent of the field displacement angle θ by the following equation:

$$R_1 = R_o + A \tan \theta$$

In this equation, R_1 is the value of R_o at the flex point of the curve and A is a constant which is a function of the ratio of cross-sections. In Fig. 2 the variation of R_1 with θ is given for 180 deg. only. When carried through the full 360 deg. the curves repeat.

The horizontal line for $S = 1$ is simply the limiting condition at which A is zero. This denotes a perfectly balanced bridge and for all other values of S the bridge is not truly balanced, since the impedances of the two coils are then unequal and the only variable is R_1. The galvanometer deflection is reduced to zero by the variation of R_1 and this partial balance is only true for a particular position of galvanometer field displacement.[1]

MANIPULATION

In using the bridge for the actual separation of specimens the method of procedure was as follows: Two specimens alike in quality and area were put in the bridge, one in each coil, and the current adjusted to the value at which the run was to be made. The bridge was balanced by means of R_1. Under these conditions the bridge balance is perfect and independent of the position of the galvanometer field. This condition is represented by the horizontal line for $S = 1$, as shown in Fig. 2. The full size specimen was now withdrawn from the test coil and another specimen of the same magnetic properties but of different cross-section was inserted in its place. This resulted in a galvanometer deflection which was reduced to zero by varying the phase of the galvanometer field without disturbing the resistance R_1 in any way. This phase angle of the galvanometer field at this point we have called θ_x.

With the galvanometer field in this position the bridge was ready for operation. Various specimens were now introduced into the test coil and if the R_1 reading necessary for balance did not change the specimens had the same magnetic properties as the standard. On the other hand a change in R_1 for balances denoted a variation in the magnetic properties of the specimens. Under these conditions the R_1 readings were a function of the quality of the material and not its cross-section. The current through the test coil was held constant during a run by varying the voltage across the bridge. The ammeter was not in circuit at the time of obtaining a balance.

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[1] See Appendix, p. 309, for further discussion of theory.

RESULTS

A number of tests were made on samples of different kinds and cross-sections, and as a practical check of the value of the method pocket knife blades of various areas were used. Two typical sets of results are reported, one on annealed strip material varying slightly in chemical composition, and the other on knife blades of varying heat treatments.

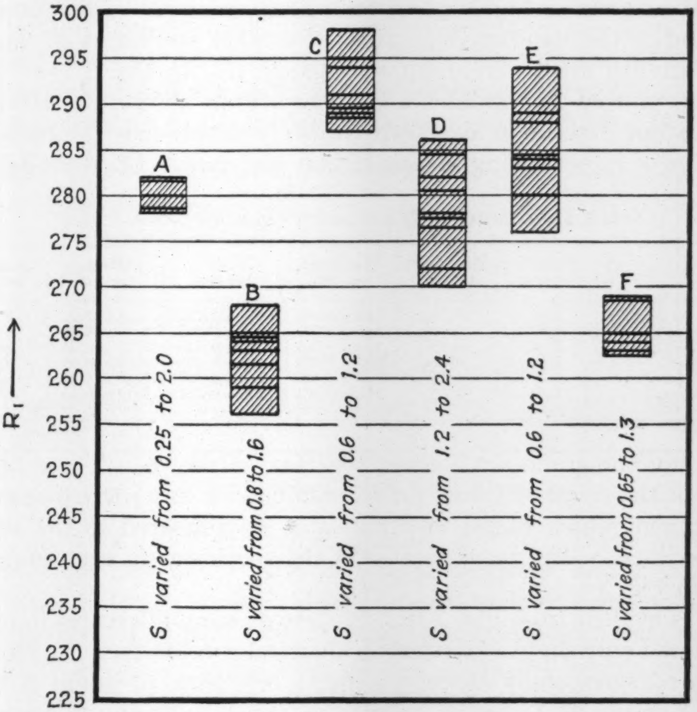

FIG. 3.—Separation of Specimens of Varying Chemical Compositions. Specimen A-1 used as standard.

Tests of Annealed Strip Material:

The six groups of specimens already mentioned were of annealed strip stock and were designated as A to F, inclusive. Their chemical composition is given in Table I, and all meet the same purchasing specifications. The hysteresis loops of these specimens showed only slight differences, none of which were sufficient to afford positive identification of any particular group.

As stated above, some of these specimens had been cut into narrow strips. They were all tested in the alternating current bridge with the galvanometer field at the θ_x position. Tests were made at different values of current and also with constant voltage across the Z_x coil. A typical set of results at a constant exciting current of 0.5 ampere are given in Fig. 3. One full size specimen, A-1 from group A, was used as the standard, and all of the other specimens of various cross-sectional areas were compared against it. In Fig. 3 the values of R_1 are plotted as ordinates and there are no abscissas. Horizontal lines one division in length are drawn to denote more prominently the value of R_1 pertaining to a particular specimen. The lines belonging to any one group are blocked together as shown. These blocks represent the range of values for R_1 obtained for any particular group of specimens which varied widely in area as compared to the standard specimen. The range in area of the specimens in each group is noted in Fig. 3.

TABLE I.—CHEMICAL COMPOSITION OF STRIP MATERIAL.

	Carbon, per cent	Manganese, per cent	Phosphorus, per cent	Sulfur, per cent	Silicon, per cent	Chromium, per cent
Group A	1.04	0.33	below 0.025	below 0.025	0.10 to 0.25	0.04
Group B	1.02	0.30	below 0.025	below 0.025	0.10 to 0.25	0.07
Group C	1.02	0.22	below 0.025	below 0.025	0.10 to 0.25	none
Group D	1.03	0.37	below 0.025	below 0.025	0.10 to 0.25	0.07
Group E	1.00	0.22	below 0.025	below 0.025	0.10 to 0.25	none
Group F	1.02	0.31	below 0.025	below 0.025	0.10 to 0.25	0.03

It is evident from Fig. 3 that in spite of wide differences in cross-section and only slight variations in chemical composition, the method segregated successfully those specimens belonging to group A from those of groups B, C and F. Some specimens belonging to groups D and E, however, are not separated from those of group A.

The difficulty confronted in the further separation of these groups, varying so little from one another, is that inherent in all methods of magnetic analysis. If the quantity, which is employed as the criterion for separation, is affected to the same or different degrees by a number of variables present, then it is possible for different combinations of these variables to give the same value for the characteristic being measured. In this particular case the variables are carbon, manganese and chromium and when two particular groups of specimens overlapped, it simply meant that the chemical constituents present affected the magnetic characteristics of the two materials in such a manner that there was no distinction between their R_1 readings. It should be kept in mind that the segregation obtained was made by means of a single reading R_1, at a given setting of the galvanometer field on four of six groups of steel, all of which met the same purchase specifications.

Tests of Knife Blades:

A number of groups of pocket knife blades in various stages of manufacture were furnished by the Winchester Repeating Arms Co., as a practical test of the method. These blades had all been cut from the same lot of stock and were in various stages of manufacture. The overall length of the blades was approximately 3.3 in., the depth 0.7 in., and the thickness before grinding 0.1 in. There were two lots of blades designated as A and B, respectively, and a standard group Nos. 70 to 75, the individual blades of each lot being numbered consecutively. Lot B and the standard group had been quenched at a temperature 50° F. higher than lot A. All of the blades, however, had been drawn at the same temperature. Blades No. 71 to 75 and group B-1 blades were heat-treated unground blades. Groups A-2 and B-2 had been rough ground and groups A-3 and B-3 were finished blades. The grinding process reduces the cross-section of the blades to slightly less than half that of the original section.

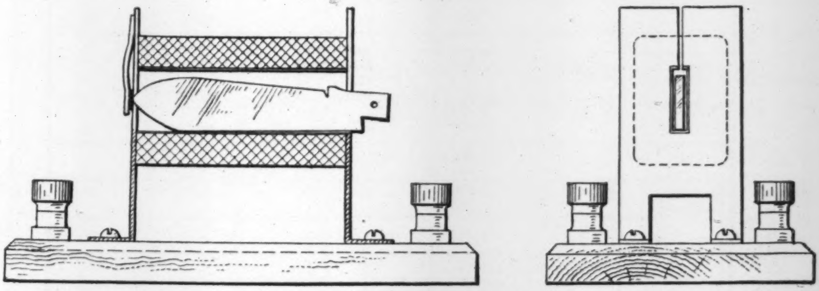

FIG. 4.—Coil for Testing Knife Blades.

Two new coils were wound identically alike to accommodate these blades; their construction is shown in Fig. 4. The winding consists of 720 turns of No. 22 D.C.C. copper wire wound on a rectangular brass shell, split along its length to avoid eddy currents. The knife blade was inserted into the coil until the point touched the stop at the rear end, in which position the tang of the blade projected out of the coil as shown. All of the blades were tested in this position. To avoid the possibility of having the blade and the brass shell form a short-circuited secondary winding of a single turn, the inside of the tube was lined with treated tape. A secondary winding was provided on the coil which contained the standard specimen.

The inductance and effective resistance of the coils were measured at 60 cycles. The insertion of an unground knife blade in the coil increased the inductance from 3.2 to 20.1 millihenrys, the resistance from 3.7 to 4.7 ohms, and the impedance from 3.9 to 8.9 ohms.

Several of the blades were broken off lengthwise to provide specimens of reduced cross-section with which to locate θ_x. The same bridge was employed as in the preceding work, the new coils merely replacing the larger ones used for the sheet steel.

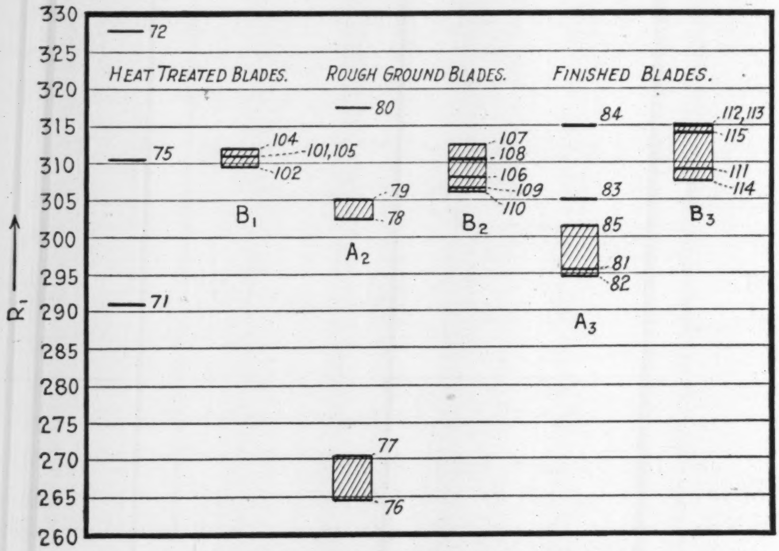

FIG. 5.—Results of Tests on Pocket Knife Blades.
Blade No. 74 used as standard.

We hardened some blades and softened others, in order to ascertain the significance of changes in the R_1 readings. Blades 71, 76 and 77 were hardened by heating them to a temperature of 1700° F. and quenching in water; blades 72 and 80 had their temper drawn by heating to a red color and then allowing them to cool slowly in air. Blades 73, 74 and 75 were normal, blade 74 was used in the standard coil, and blade 73 was broken to reduce its cross-section.

In Fig. 5 are presented typical results, the values being plotted in the same manner as in Fig. 3. The numbers to the right of the lines denoting the R_1 readings are the code numbers of the blades. The

Brinell hardness tests were made with a Baby Brinell Tester, using a $\frac{3}{32}$-in. diameter ball under a 170 kg. load.

The effect of a softened blade is to increase the value of R_1 in comparison to the normal reading, and that of a hardened blade to decrease its value. This is clearly shown by the location of the softened blades, Nos. 72 and 80, and the hardened blades, Nos. 71, 76 and 77.

The blades are listed in Table II in ascending order of their R_1 readings together with the corresponding Brinell hardness numbers. In general, considering the localized character of the Brinell hardness numbers there is agreement between them and the magnetic results.

TABLE II.—TESTS OF KNIFE BLADES.

Lot A				Lot B			
Blade	R_1 Reading	Brinell Hardness Numbers		Blade	R_1 Reading	Brinell Hardness Numbers	
		Point	Body			Point	Body
No. 71...........	291.0	...	657+	No. 102.........	309.5	426	592
No. 75...........	310.5	544	572	No. 101.........	311.0	380	572
No. 72...........	328.0	...	254	No. 105.........	311.0	396	592
				No. 104.........	312.0	396–408	408
No. 76...........	264.5	...	...	No. 110.........	306	....	600
No. 77...........	270.5	...	657	No. 109.........	306.5	380–408	592
No. 78...........	302.5	...	592	No. 106.........	308.0	600	623
No. 79...........	305.0	592	623	No. 108.........	310.5	426	600
No. 80...........	317.5	...	225	No. 107.........	312.5	592	600
No. 82...........	294.5	592	623	No. 114.........	307.5	592	600
No. 81...........	295.5	592	600	No. 111.........	309.0	592	623
No. 85...........	301.5	572–592	...	No. 115.........	314.0	592	572
No. 83...........	305.0	503–519	623	No. 112.........	315.0	572	592
No. 84...........	315.0	355	426	No. 113.........	315.0	396	355–365

The relative degrees of hardness in blades No. 71 to 75 and group A-2 is at once apparent.

The blades in group B-1 are very close together magnetically and the Brinell hardness numbers are also quite close, with the exception of blade No. 104, whose Brinell number is 408. The R_1 reading indicates that this blade is the softest of the group, but from the Brinell hardness value it should be higher and further displaced from the others. The magnetic and Brinell hardness results check throughout for the blades in group B-2.

The finished blades in group A-3 were all supposed to be standard. The magnetic test, however, showed that blades Nos. 84 and 83 were soft, particularly No. 84. The Brinell hardness test revealed that blade No. 84 was considerably softer than normal and that in the case of No. 83, although its body was of normal hardness, its point was soft. In the group of finished blades B-3, the R_1 values for blades

Nos. 112 and 113 were the same, although the Brinell hardness test indicates that No. 113 is the softer of the two.

With the exception of two blades, Nos. 104 and 113, there is a good correlation between the magnetic results and the Brinell hardness numbers. The R_1 value is quite distinct and is affected by the entire body of the blade in the test coil, whereas the Brinell hardness number is a function only of the hardness of the material under the ball. It is also interesting to note that the magnetic test results bring out the difference in the quenching temperatures of the two lots of blades, although their Brinell hardness numbers are the same.

This test on knife blades also shows clearly the independence of the bridge results of differences in area. The blades in the standard and B groups had all received the same heat treatment, but the standard blade and those in group B-1 were of unground cross-section. The grinding, sharpening and polishing operations are supposed to be carried out in such a manner as to preserve the temper of the blades. The data of Fig. 5 shows that group B-2, which had been ground, and B-3, which had in addition been sharpened and polished, retain their physical properties.

In the tests that have been reported in this paper, the current in the test coil was maintained constant at 0.5 ampere. Other values of current were used and measurements were also carried out maintaining the voltage across the test coil constant. The relative separation attained under these conditions was the same as that with the constant current of 0.5 ampere. Furthermore, it was found that when the bridge was once adjusted for a normal test specimen, the balance was not upset by the small change in current through the test coil caused by the variation in R_1, necessary to balance for a non-standard specimen. This means that measurements could be made on various specimens without readjusting the current for each new balance point, that is, the testing could be performed with a constant voltage across the bridge.

With the bridge balanced for two normal blades, the frequency of the supply was varied from 49 to 83 cycles without disturbing the balance. Hence it may be said that when operating the bridge at 60 cycles the ordinary frequency fluctuations do not affect the separation.

CONCLUSIONS

The following conclusions may be drawn from this investigation:

1. An "unbalanced" alternating current bridge using an alternating current galvanometer has been developed for magnetic testing. In this bridge there is a certain position of the phase of the galvano-

meter field at which the bridge balance depends only upon the relative magnetic qualities of the specimens compared, and not upon the area of their cross-sections, within the range studied.

2. Data have been presented showing that segregation has been attained between standard and non-standard specimens, with the cross-section of the test specimen varying from one-quarter to twice that of the standard specimen, the lengths remaining constant.

The investigation is being continued and it is hoped that the complete theory will be developed and additional data secured for presentation in a later paper.

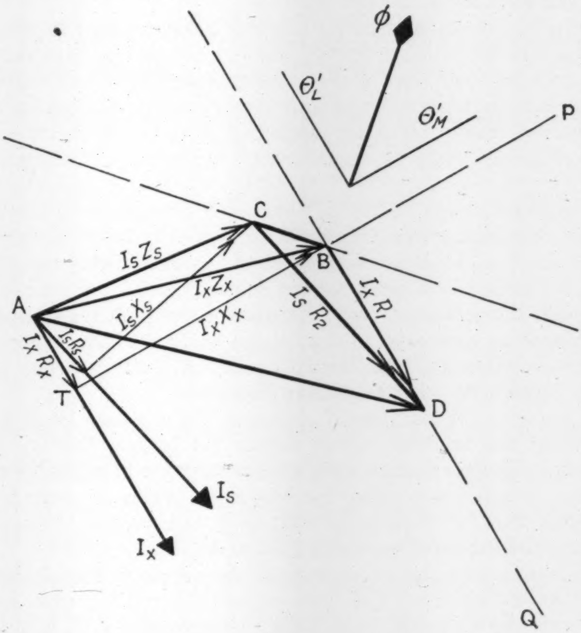

FIG. 6.—Vector Diagram of Bridge Circuit.

Acknowledgment.—The authors wish to express their sincere appreciation to the Winchester Repeating Arms Co. for furnishing the test specimens, making the chemical analyses and Brinell hardness measurements and for their whole-hearted cooperation throughout the entire course of this work.

APPENDIX

Further Discussion of Theory:

The behavior of the bridge may be readily understood from its vector diagram, Fig. 6. Here I_s and I_x represent the currents through the standard and test coils respectively. The current I_x was maintained constant at 0.5 ampere by varying the applied voltage. Hence for a given ratio of sections the impedance drop AB across the test coil was fixed. The vector AC equals the impedance drop across the standard coil. If the ratio of the cross-sections of the two specimens is unity and their magnetic qualities are alike, the points B and C will coincide, I_x and I_s will be in phase, the respective resistance drops I_xR_1 and I_sR_2 will be equal and in phase. Under these conditions the bridge will be perfectly balanced for all positions of the galvanometer field. If, however, either the cross-sections are unequal or the magnetic characteristics unlike, the points B and C will not coincide and there will be an unbalanced vector BC across the galvanometer terminals.

The deflection of an alternating current galvanometer is proportional to that component of the current flowing through its moving element which is in phase with the field flux; that is, in vector representation the deflection is proportional to the projection of the current vector on the field flux vector. Therefore, if the galvanometer field, represented by Φ, is in the position as shown in the diagram, it is necessary to vary R_1 until the vector CB assumes a position at right angles to Φ.

When the unbalanced vector CB has been brought to a position at right angles to the field, the galvanometer deflection is reduced to zero, but there will remain a small quadrature component of current flowing through the moving element. This galvanometer current is less than 0.2 per cent of the current flowing through the specimen coils, because of the high resistance of the galvanometer circuit as compared to that of the bridge. This quadrature current may therefore be neglected and the I_sR_2 and I_xR_1 voltage drops may be considered as in phase with their respective currents.

As the current I_x is maintained constant, the variation of R_1 necessary for balance modifies the applied voltage across the bridge, thereby also varying the current I_s. However, since I_xR_1 always remains in phase in the I_xR_x the terminal point D will move along the line BQ. When R_1 has been adjusted to such a value that CB is perpendicular to Φ, the applied voltage AD will be determined by the intersection, D, of I_sR_2 and I_xR_1.

The explanation for the asymptosy of the curves in Fig. 2 may be readily seen in the vector diagram. The lines marked θ'_L and θ'_M represent Φ when it is in phase with the loss and magnetizing components I_xR_x and I_xX_x, respectively. Now as Φ approaches the position θ'_L the unbalanced vector CB, which is kept in quadrature with Φ by adjustment of R_1, approaches parallelism with the line TBP; this means that I_sR_2 becomes more nearly parallel with I_xR_1 and the intersection of their two resistance drops, D, moves further out along BQ. When Φ lies in the position marked θ'_L then C must fall on the line TBP on one or the other side of B; C cannot coincide with B because the impedances Z_s and Z_x are unequal. However, in this case the resistance drops CD and BD would be parallel and therefore under this condition it would be impossible to have the intersection D. This means that with Φ along θ'_L the galvanometer deflection cannot be reduced to zero. This also explains why as Φ approaches θ'_L the values of R_1 for balance increase so rapidly and tend to become infinite at θ'_L.

The lines θ'_L and θ'_M on the vector diagram are the theoretical positions. The points in Fig. 2 marked θ_L and θ_M are those obtained experimentally by means of the secondary winding and do not coincide with the theoretical positions by reason of the fact that the applied voltage on the test coil is not exactly 180 deg. out of phase with the induced voltage due to the power factor of the circuit. The unbalanced vector, *BC*, may be expressed as:

$$\dot{E}_{BC} = \dot{I}_x R_1 - \dot{I}_s R_2$$

Expanding this and substituting the value of I_s in terms of I_x gives:

$$\dot{E}_{BC} = \frac{\dot{I}_x R_1 (R_2 + R_s + jX_s) - \dot{I}_x R_2 (R_1 + R_x + jX_x)}{R_2 + R_s + jX_s}$$

For zero galvanometer deflection with unequal specimens the vector *BC* must be perpendicular to the phase of the galvanometer field Φ. The value of R_1 required to satisfy this condition was determined from the above relation, and the phase, θ, of the field and is given by the equation:

$$R_1 = \frac{R_2(R_2 R_x + R_s R_x + X_s X_x) - R_2(R_s X_x + R_2 X_x - R_x R_s) \tan\theta}{Z_s^2 - R_2^2 - R_s R_2 - R_2 X_s \tan\theta}.$$

where R_x, R_s, X_x and X_s are the effective resistances and reactances of the test and standard coils, respectively, when the specimens are within the coils.

Attempts to express R_1 as a function of the cross-sections of the standard and unknown specimens have thus far been unsuccessful.

DISCUSSION

MR. L. W. MCKEEHAN.[1]—I want, first, to compliment the authors on devising a magnetic analysis method independent of external dimensions; also I want to comment on the physical characteristics of the metal that must be considered in reviewing these results of *magnetic* analysis. I suppose that D. E. Hughes, about 1880, was the first person to use an alternating current bridge in comparing two pieces of metal. He used the telephone as a detector, and he did not, in most of his experiments, compare magnetic materials at all. He compared, for example, coin silver with debased coinage. He reasoned that he could find differences between the two pieces of metal by this method because their resistivities were different and the modifications of the magnetic field in the coins by the eddy currents in the specimens were different. The same effect must be an important one here, because even the lowest frequency mentioned, forty-nine cycles, is not low enough to give uniform magnetization in the sections mentioned. If there is a considerable skin effect, the fact that the magnetization does not penetrate completely to the center of the piece is indicated, I believe, by the transfer of the point θ_x to different places with different lots of material. The combination then of magnetic properties and resistivity is really under consideration, and that, I think, explains the few erratic results. These are apparently connected with superficial differences, such, for example, as would be created by changing the hardness of the knife point, and are accompanied by variations in Brinell hardness in surface tests. In fact, the chance of getting variations by this method is much greater than the chance of getting variations by a static magnetic test, as the authors themselves point out; the magnetization curves for different lots were not very different, not as different as the results of this test alone would indicate.

I think we should keep in mind in considering the use of the method that anything which changes resistivity is likely to modify the results it yields.

MR. W. B. KOUWENHOVEN[2] (*author's closure by letter.*)—Mr. McKeehan's comments are very valuable and we realize that the phenomena in question is partly caused by the resistivity of the material as well as its magnetic properties. Without doubt, skin effect plays a part in these results and further tests have indicated that in order to secure complete penetration we must reduce the frequency to a much lower value.

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INVESTIGATION OF COLD-DRAWN BRIDGE WIRE

By L. S. Moisseiff[1]

Synopsis

The Detroit River Bridge, known as the Ambassador Bridge, is at the present time the longest span bridge in the world. It is a suspension bridge with a span of 1850 ft. The cables are of cold-drawn wire and contain over 16,000 wires and weigh 3000 tons. The Mount Hope Bridge is a span of 1200 ft.; the cables contain 2400 wires and weigh 700 tons. The same wire was used for both bridges. The contractor for these bridges, the McClintic-Marshall Co., organized a series of tests of the wire. The program intended to cover all practical questions in connection with the strength and behavior of this wire during its storing, erection of the cables, and thereafter as part of the bridge under dead and live loads and climatic conditions. The tests were made at Lehigh University. They covered verification of acceptance tests at the mill, determination of physical qualities, such as modulus of elasticity, shape of stress-strain curve, proportional limit, ultimate strength, elongation and reduction of area, as well as uniformity along a coil. Study was made of behavior of wire in conditions simulating those existing in the bridge under load. Creep or fatigue tests under loads up to one and one-half times the design stress and of a duration of two months, as well as freezing tests were carried out. Study was made of the effect of mishandling the wire during shipping and erection as well as effect of wedging action. A study was made of the metallurgical characteristics. The tests present as complete a set of tests on wire for bridge purposes as has as yet been made. The duration tests under static loads are novel. The results are very satisfactory and furnish assurance to bridge builders on the reliability of wire for large structures.

The bridge at Detroit over the Detroit River is known as the Ambassador Bridge. It is a single span suspension bridge with the usual suspended stiffening truss. It has a span of 1850 ft. and is at the present time the longest span bridge in operation. It soon will be surpassed by the Hudson River Bridge now under construction, with a span almost double in length, namely, 3500 ft. The Hudson River Bridge, in turn, promises to be eclipsed by the 4200-ft. span of the Golden Gate Bridge at San Francisco, preliminary plans for which are now in preparation. The Ambassador Bridge has two cables, each of 8066 wires, No. 6 gage, laid parallel. The cables are laid continuous over the two towers and anchored at the end by means of eyebars and beams in concrete anchorages. The total weight of the wire in the cables is 3000 tons.

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The Mount Hope bridge at Narragansett Bay, R. I., is a three-span suspension bridge with a center span of 1200 ft. It has two cables, each of 1200 wires, No. 6 gage, with a total weight of 700 tons.

Wire for bridge cables has been in use for over a century and millions of acceptance tests have been made for the construction of bridges. The accumulated experience of many years has shown that cables of bridge wire are the most dependable members of a bridge. Tests to determine one or another characteristic of bridge wire have been made in the past, noticeably the tests of wire for the Delaware River bridge at Philadelphia in 1921 and 1922.

After it had been decided to replace the cables of the heat-treated wire in the Detroit River and Mount Hope bridges by cold-drawn wire, the McClintic-Marshall Co., who were the contractors for these bridges, wished to make a complete investigation of the cold-drawn wire which the American Cable Co. were supplying for the cables of these bridges. Mr. Jonathan Jones, Chief Engineer of the McClintic-Marshall Co., in consultation with Mr. W. A. Slater, Mr. Bradley Stoughton and the author, laid out a program of investigations and tests. The tests were made in 1929 at Lehigh University. W. A. Slater conducted the physical tests and Bradley Stoughton the metallurgical investigations.

MATERIALS

The specifications for the wire for the Ambassador and Mount Hope bridges were as follows:

All steel shall be made in an acid open-hearth furnace. On ladle test the steel shall show not more than the following percentages of elements:

Carbon, per cent	0.85
Sulfur, per cent	0.04
Phosphorus, per cent	0.04

Check analyses may be made by the engineer and shall not show an excess beyond the specified limits for such elements, of more than 10 per cent in the case of carbon and 25 per cent in the case of phosphorus and sulfur.

The wire billets shall be cut into uniform lengths, weighing not less than 225 lb.

The wire before galvanizing shall measure normally 0.192 in. in diameter and shall not vary more than ±0.003 in. It shall be finished in single lengths of not less than 2000 ft. The bright wire shall coil around a rod one and one-half times its own diameter, without signs of fracture.

Specimens cut from the galvanized wire shall show the following physical properties:

Tensile strength, lb. per sq. in., of gross cross-section, minimum	215 000
Yield point, lb. per sq. in., minimum	144 000
Elongation in 10 in. while under tension, per cent, minimum	4

The yield point shall be determined by a reading taken when the specimen has elongated 0.75 per cent in an original length of 10 in. This test shall be made on every fifth coil.

Galvanized wire shall not measure more than 0.005 in. larger in diameter than the bright wire and shall be capable of coiling continuously around a mandrel 2 in. in diameter, without developing the galvanizing cracks visible to the naked eye.

TABLE I.—CHEMICAL ANALYSIS OF WIRE FROM MILL RECORDS.

Coil		Heat Number	Used in Specimens	Ladle Analysis				
Laboratory Number	Field Number[a]			Carbon, per cent	Manganese, per cent	Phosphorus, per cent	Sulfur, per cent	Silicon, per cent
1	72W121	121	All of Series Nos. 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14.	0.78	0.58	0.024	0.035	0.19
2	72W122	122		0.80	0.57	0.022	0.032	0.18
3	72W123	123		0.80	0.58	0.028	0.036	0.16
4	165	165	1.1, 2.1	[b]	....	.....	.....	....
5	166	166	1.2, 2.2	[c]	....	.....	.....	....
6	167	167	1.3, 2.3	[b]	....	.....	.....	....
7	168	168	1.4, 2.4	0.77	0.48	0.038	0.036	0.15
8	1	...	1.5, 2.5	[d]	....	.....	.....	....
9	1A	...	1.6, 2.6	[d]	....	.....	.....	....
10	A	...	1.7, 2.7	[d]	....	.....	.....	....
11	B	...	1.8, 2.8	[d]	....	.....	.....	....
12	A	...	1.9, 2.9	[d]	....	.....	.....	....
13	B	...	1.10, 2.10	[d]	....	.....	.....	....
14	1	...	1.11, 2.11	[d]	....	.....	.....	....
15	2	...	1.12, 2.12	[d]	....	.....	.....	....
16	72W140	140	9.1	0.77	0.52	0.031	0.037	0.13
17	72W125	125	9.2	0.80	0.55	0.025	0.035	0.10
18	72W139	139	9.3	0.76	0.55	0.028	0.039	0.14
19	72W118	118	9.4	0.76	0.60	0.025	0.033	0.18
20	72W130	130	9.5	0.79	0.55	0.022	0.031	0.19
21	$\frac{30}{\text{72W156}}$	156	9.6	0.77	0.53	0.030	0.035	0.19
22	$\frac{55}{\text{72W154}}$	154	9.7	0.74	0.57	0.027	0.032	0.20
23	$\frac{137}{\text{72W162}}$	162	9.8	0.74	0.48	0.031	0.030	0.20
24	72W146	146	9.9	0.78	0.56	0.025	0.035	0.17
25	$\frac{5}{\text{72W206}}$	206	9.10	0.75	0.54	0.035	0.031	0.20
	$\frac{45}{\text{72W127}}$	127	Series No. 14	0.76	0.52	0.023	0.035	0.16
	$\frac{126}{\text{72W129}}$	129	Series No. 14	0.77	0.50	0.025	0.035	0.18
	$\frac{64}{\text{72W123}}$	123	Series No. 14	0.80	0.58	0.028	0.036	0.16
	$\frac{128}{\text{72W119}}$	119	Series No. 14	0.80	0.62	0.031	0.040	0.13
	$\frac{191}{\text{72W115}}$	115	Series No. 14	0.76	0.58	0.027	0.035	0.19

[a] In the Field No. 72W is the steel mill's designation for the order and the last three digits are the heat number.
[b] Analysis not furnished by steel mill.
[c] Rejected at mill.
[d] Analysis not available because heat number was not identified.

Samples not less than 8 in. long shall be subjected to a Preece test for galvanizing, at the request of the inspector, but not on less than 5 per cent.

The cable wire shall be spliced with a sleeve joint not more than $\frac{11}{32}$ in. in outside diameter and capable of developing 95 per cent of the ultimate specified strength of the wire.

Wire for the two bridges was taken from the same stock as required.

The wire used in these tests was representative material selected from wire accepted for use in the bridges. It was taken at intervals during its production. The mill tests of this wire are given in Tables I and II. As shown by the mill tests, the material met the requirements of the specifications for carbon, sulfur and phosphorus content. Analyses for carbon by Stoughton on three specimens from three ingots met the carbon requirements of the specification. Of the approximately 300 tension tests made, only 4 specimens (0.13 per cent) showed tensile strengths less than the specified value of 215,000 lb. per sq. in.; the lowest found was 212,000 lb. per sq. in. Approximately 45 yield point determinations were made. All of these met the specification requirement of at least 144,000 lb. per sq. in. at a tensile strain of 0.75 per cent.

TABLE II.—PHYSICAL TESTS OF WIRE FROM MILL RECORDS.

Coil		Heat Number	Used in Specimens	Diameter, in.		Strength, lb. per sq. in.		Strength at 0.75 per cent Elongation, lb. per sq. in.		Elongation, per cent	
Laboratory Number	Field Number[a]			Specimen A[b]	Specimen B[b]	Specimen A[b]	Specimen B[b]	Specimen A[b]	Specimen B[b]	Specimen A[b]	Specimen B[b]
21.....	30/72W156	156	9.6	0.194	0.194	226 000	221 900	169 800	172 500	6.0	5.6[c]
22.....	55/72W154	154	9.7	0.194	0.194	225 300	224 000	166 400	164 800	6.1[c]	6.6[c]
23.....	137/72W162	162	9.8	0.194	0.195	219 900	217 000	......	......	5.8	5.4[c]
25.....	5/72W206	206	9.10	0.195	0.195	223 000	219 700	168 100	167 700	6.8[c]	6.7
	45/72W127	127	Series No. 14	0.194	0.195	230 700	229 400	177 300	172 100	6.7[c]	6.6[c]
	126/72W129	129	Series No. 14	0.194	0.194	228 000	228 400	......	......	6.0[c]	5.6[c]
	64/72W123	123	Series No. 14	0.194	0.195	230 400	228 400	......	......	6.1[c]	6.2
	128/72W119	119	Series No. 14	0.196	0.196	237 300	230 000	......	......	6.4	6.6[c]
	191/72W115	115	Series No. 14	0.195	0.195	236 900	230 700	......	......	5.8[c]	6.2

[a] In the Field No. 72W is the steel mill's designation for the order and the last three digits are the heat number.

[b] Specimens A and B represent specimens at opposite ends of coil. Usually Specimen B is the end last drawn.

[c] Wire broke outside of 10-in. gage length.

NOTE.—Physical tests on other coils listed in Table I are not available.

The elongation of the wire was measured over gage lengths of 2 and 8 in., instead of 10 in. as given in the specifications. In most cases the elongation over the gage length used was sufficiently in excess of 4 per cent to indicate the elongation in 10 in. would not be less than 4 per cent. In three cases the elongation in 8 in. was less than 4 per cent and in about eight others it was so close to 4 per cent that the elongation in 10 in. would possibly be less than 4 per cent. This is out of a total of 45 tests.

TESTING MACHINES AND APPARATUS

Tension tests which were continued directly to failure were made in 50,000-lb. Riehle testing machines. The machines were calibrated with proving levers and dead weights to a load of 20,000 lb. One machine had an error of approximately ±0.1 per cent and the other of about 0.4 per cent for loads about 12,000 lb. and somewhat more than this for lower loads.

For the long-time tension tests, 12 special machines were built. They are shown in Fig. 1. Where wires were tested over sheaves, these were made of semi-circular steel sheaves with a diameter of 19½ in. and were free to rotate on a 2-in. shaft as the center bearing. The sheave had a longitudinal groove rectangular in cross-section, and wide enough to seat two wires side by side. The test specimen had its bearings on the sheave throughout an angle of 180 deg. The straight portion of the wire, or the tangent, which extended from the sheave to the end clamps was vertical. The sheave was made of a circular sector of a little greater than 180 deg. to avoid sharp bending in the wire at the points of leaving the sheave.

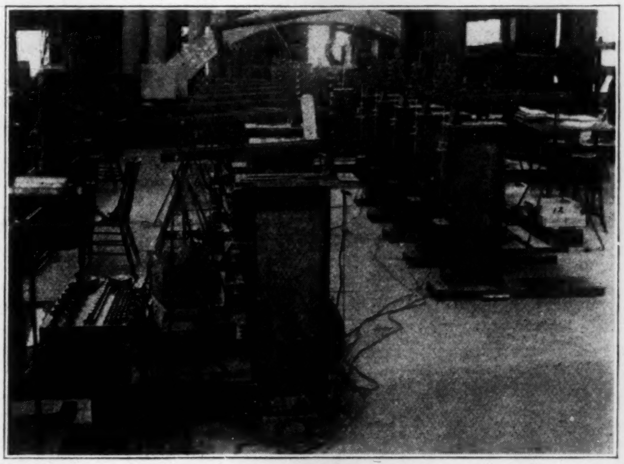

FIG. 1.—View of Special Wire-Testing Machines.

For the most part, a Ewing extensometer with a gage length of 8 in. was used for measuring the strains in the tests which were carried to immediate failure. For comparison, in a few cases Huggenberger

TABLE III.—CONFIRMATORY ACCEPTANCE TENSION TESTS—SUMMARY OF RESULTS OF SERIES NO. 1.

Specimen		Diameter, in.	Proportional Limit, lb. per sq. in.[a]	Stress at 0.75 per cent Elongation, lb. per sq. in.	Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Modulus of Elasticity, lb. per sq. in.
Laboratory Number	Field Number							
1.1..........	165-2	0.195	100 000	174 500	219 300	9.0	33.0	28 800 000
1.2..........	166-2	0.196	90 000	179 000	229 100	9.0	32.0	29 000 000
1.3..........	167-2	0.197	110 000	171 500	216 500	8.5	36.0	27 200 000
1.4..........	168-2	0.196	100 000	169 200	211 500	10.0	33.0	28 000 000
1.5..........	1	0.195	110 000	173 600	215 300	....	21.0	27 200 000
1.6..........	1A	0.195	100 000	173 000	216 600	5.0	28.0	26 900 000
1.7..........	A	0.194	100 000	170 000	213 300	6.2[b]	32.0	27 500 000
1.8..........	B	0.196	110 000	173 400	216 200	3.7[b]	11.6	28 160 000
1.9..........	A	0.196	100 000	170 000	217 100	6.9[b]	33.0	27 660 000
1.10..........	B	0.196	100 000	176 000	225 000	6.3[b]	29.0	28 200 000
1.11..........	1	0.196	110 000	173 000	221 900	5.6[b]	30.0	27 600 000
1.12..........	2	0.197	110 000	179 000	217 600	7.5[b]	25.5	27 700 000
Average....	....	0.196	103 300	173 500	218 280	8.3 6.0[b]	28.7	27 826 600
High.......	....	0.197	110 000	179 000	229 100	10.0 7.5[b]	36.0	29 000 000
Low.......	....	0.194	90 000	169 200	211 500	5.0 3.7[b]	11.6	26 900 000

[a] Proportional limit determined by divergence of stress-strain curve from tangent.
[b] Elongation in 8 in.
NOTE.—All fractures were silky cups.

TABLE IV.—CONFIRMATORY ACCEPTANCE TENSION TESTS—SUMMARY OF RESULTS OF SERIES NO. 2.

Specimen		Diameter, in.	Proportional Limit, lb. per sq. in.[a]	Stress at 0.75 per cent Elongation, lb. per sq. in.	Load at which set began, lb. per sq. in.	Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Modulus of Elasticity, lb. per sq. in.
Laboratory Number	Field Number								
2.11......	165-3	0.195	115 000	173 000	110 000	212 950	7.5	35.0	27 600 000
2.2......	166-3	0.195	120 000	177 500	110 000	233 400	9.0	28.0	27 600 000
2.3......	167-3	0.197	105 000	176 000	100 000	217 800	9.0	32.0	28 000 000
2.4......	168-3	0.195	120 000	177 500	110 000	220 900	9.5	33.0	28 300 000
2.5......	2	0.195	100 000	174 500	90 000	215 900	8.5	29.0	28 000 000
2.6......	2A	0.195	110 000	177 000	110 000	222 300	8.5	26.0	28 500 000
2.7......	A	0.195	110 000	169 500	90 000	212 000	5.6[b]	27.0	27 740 000
2.8......	B	0.196	100 000	172 500	90 000	215 100	5.6[b]	16.0	28 060 000
2.9......	A	0.197	100 000	171 500	100 000	221 500	4.4[b]	26.0	27 880 000
2.10.....	B	0.196	110 000	178 000	110 000	225 400	5.0[b]	23.0	28 760 000
2.11.....	1	0.196	110 000	174 000	100 000	223 560	6.2[b]	37.0	27 680 000
2.12.....	2	0.197	120 000	180 000	110 000	227 360	6.7[b]	29.0	28 060 000
Average.	......	0.196	110 000	175 080	102 910	220 680	8.7 5.6[b]	28.4	28 015 000
High....	......	0.197	120 000	180 000	110 000	233 400	9.5 6.7[b]	37.0	28 760 000
Low....	......	0.195	100 000	169 500	90 000	212 000	7.5 4.4[b]	16.0	27 600 000
2.13.....	72121	0.195	110 000	178 000	100 000	225 900	4.4[b]	19.4	27 600 000
2.14.....	72121	0.195	120 000	177 000	110 000	222 000	5.6[b]	18.5	27 900 000
2.15.....	72122	0.195	110 000	180 000	110 000	229 100	4.4[b]	18.5	27 600 000
2.16.....	72122	0.195	115 000	183 000	115 000	229 700	2.5[b]	24.9	28 200 000
2.17.....	72123	0.195	115 000	170 000	95 000	219 400	4.4[b]	30.1	27 200 000
2.18.....	72123	0.193	110 000	170 000	90 000	223 900	4.4[b]	28.7	26 800 000

[a] Proportional limit determined by divergence of stress-strain curve from tangent.
[b] Elongation in 8 in.
NOTE.—All fractures were silky cups.

tensometers, type C, gage length of 1 in., were used. Strains for the modulus of elasticity tests under dead load were measured over a gage length of 96 in. by Ames gages. The Huggenberger tensometers measured the strain on the surface of the specimen. Two were placed opposite each other and the average was used.

In measuring the strains for the long-time tests, electric telemeters,[1] shown in Fig. 1, were used.

CONFIRMATORY ACCEPTANCE TESTS

Tension tests of 12 individual wires, Series No. 1, were made to determine the modulus of elasticity, shape of the stress-strain curve, the proportional limit, yield stress at elongation 0.75 per cent, tensile strength, ultimate elongation and reduction of area. These wires were selected at intervals during the period of production of the wire and were shipped to the laboratory unstraightened. The samples were 24 in. long and were fastened together in pairs from the same coil, so that tests in two series could be made from identical wire.

Tension tests were also made to determine the stress at which permanent elongation began. In this test the wire was subjected to stresses progressively increasing to about 80,000 lb. per sq. in. The load was then decreased to the initial load about 13,000 lb. per sq. in., the extensometer was read and the greater load applied. This procedure was repeated until load-set and load-strain curves were obtained. The specimens of this series were from the same coil as Series No. 1 and the corresponding results of the two series are directly comparable.

The results of the acceptance tests, Series Nos. 1 and 2, are given in Tables III and IV. For each specimen test in Series No. 1, a specimen, plotted at the same place, was tested in Series No. 2. Therefore, a close agreement should be expected in the results of the two tables. That there was a good agreement is evident from the comparison of average values. Variation between average of Series No. 1 and Series No. 2 is as follows:

	VARIATION, PER CENT
Proportional limit	3.1
Tensile strength	0.55
Stress at 0.75 per cent elongation	0.43
Elongation in 2 in.	2.4
Elongation in 8 in.	3.3
Reduction of area	0.53
Modulus of elasticity	0.34

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[1] These electric telemeters are described in U. S. Bureau of Standards *Technologic Paper No 247*, and in the "Report of Tests on Stevenson Creek Arch Dam," *Proceedings*, Am. Soc Civil Engrs., May, 1928, Part III, p. 71.

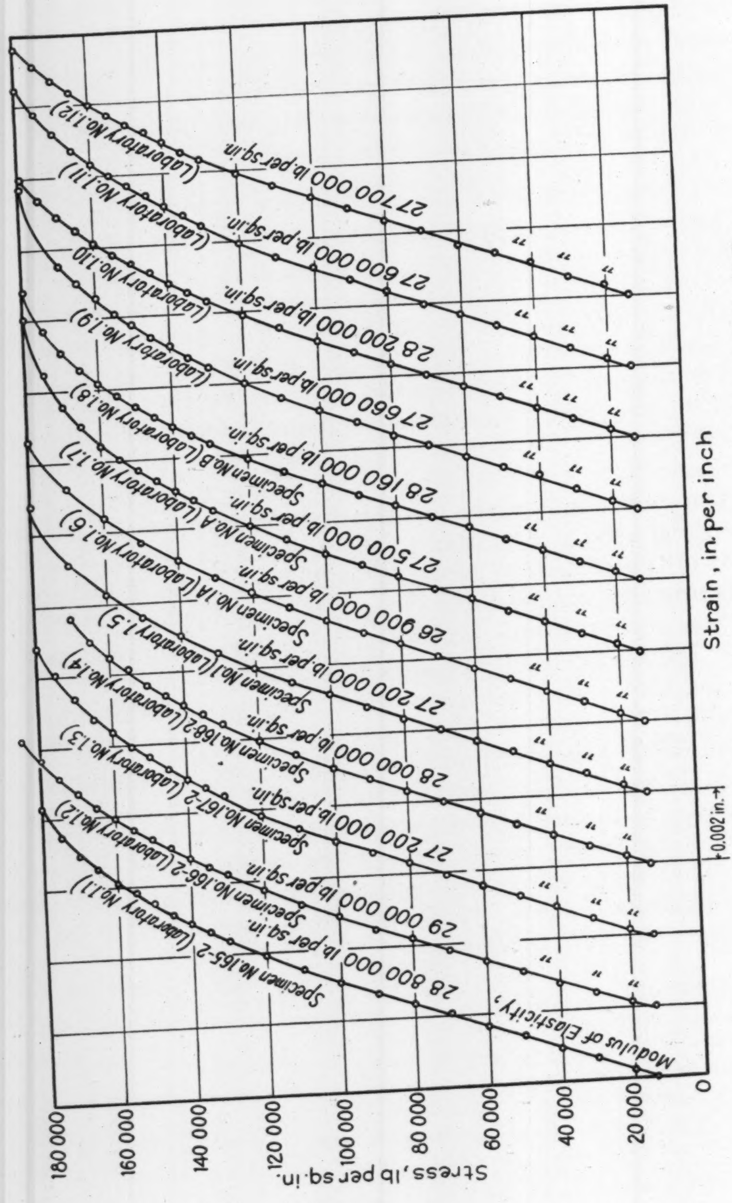


FIG. 2.—Stress-Strain Curves from Tension Tests of Detroit Bridge Wire, Series No. 1.

The proportional limit for Series No. 1 was 103,300 lb. per sq. in. and the load at first set for Series No. 2 was 102,900 lb. per sq. in. The difference is only 0.2 per cent of the average. Figures 2, 3 and 4 show the stress-strain curves for Series Nos. 1 and 2. The proportional limit was the stress at which the stress-strain curve departed noticeably from a straight line. Obviously the observed point of departure will depend partly upon the scale to which the strains are

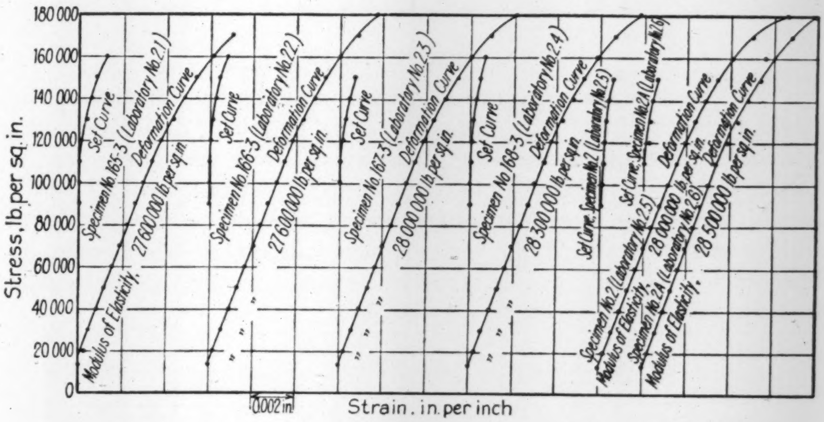


FIG. 3.—Stress-Strain Curves from Tension Tests of Detroit Bridge Wire, Series No. 2.

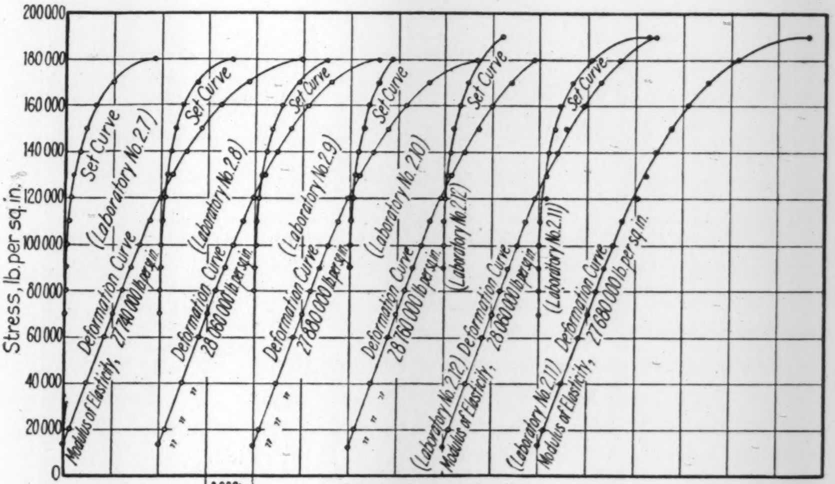


FIG. 4.—Stress-Strain Curves from Tension Tests of Detroit Bridge Wire, Series No. 2.

plotted and partly upon the accuracy with which they were measured. The agreement of the two series is an indication that the stress at first set may be taken as a close measure of the proportional limit.

UNIFORMITY TESTS

Tests were made to secure information on the uniformity of the tensile strength of the wire throughout the length of any given coil. Specimens were taken at intervals of about 10 ft. along the length of each coil. To these tests may be added the results of all other tests in which the specimens were tested straight, and directly to failure, and into which no variable was introduced which may be expected to affect the tensile strength. The summary of the tensile strengths of these tests is given in Table V.

TABLE V.—UNIFORMITY OF TENSILE STRENGTH.

Series	Number of Specimens	Average Tensile Strength, lb. per sq. in.	Probable Variation of the Average Strength, lb. per sq. in.	Maximum Variation of any strength from average, per cent
No. 1	12	218 300	....	....
No. 3*B*	6	226 500	....	....
No. 8 coil 1	43	224 400	±101	1.0
No. 8 coil 2	43	230 900	±129	1.5
No. 8 coil 3	43	227 500	±113	0.75
Average weighted according to number of tests	....	226 800	....	....

RATE OF CREEP IN LONG-TIME TESTS

Long-continued tests were made to discover any creep, that is, increase in strain under a constant load, or fatigue in tensile stress, at loads up to 50 per cent greater than the bridge design stress. These tests are designated Series Nos. 3, 4, and 5.

In Series No. 3*A*, one wire from each of three coils was suspended straight from clamps and loaded by dead weight. The load started at approximately 76,000 lb. per sq. in. and was increased daily by 19,000 lb. per sq. in. until approximately 114,000 lb. per sq. in. was reached; this load was left for two weeks, observing with an electric telemeter for any creep and the specimen was then tested to failure.

In Series No. 3*B*, one wire from each of three coils was similarly suspended and loaded straightway to failure for comparison with the results of the long-time tests in Series Nos. 3*A* and 3*C*.

In Series No. 3*C*, one wire from each of three coils was tested in the same manner as in Series No. 3*A*, except that the load of approximately 114,000 lb. per sq. in. was retained for two months.

Series No. 4 was similar to Series No. 3 except that the wires were suspended over a $19\frac{1}{2}$ in. diameter sheave with a clamp at one end and a loading platform at the other. The wires as placed over the sheaves without any pre-shaping were bent in the direction of their natural coiling curve.

Series No. 5 was identical with Series No. 4, except that the wires as placed on the sheaves were bent in the reverse direction of their natural coiling curves.

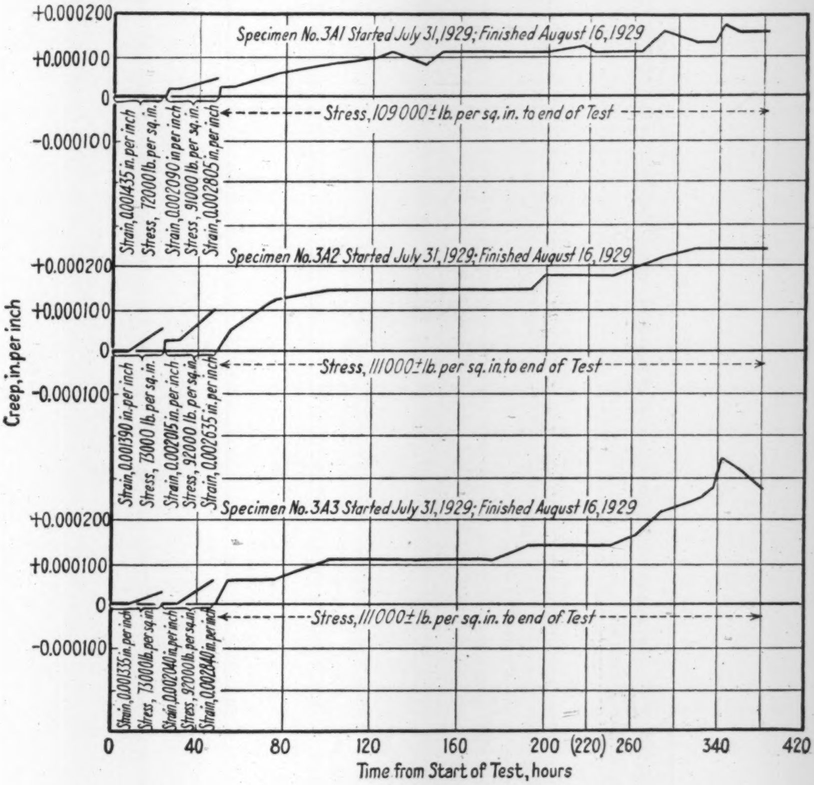


FIG. 5.—Creep Curves, Series No. 3*A*.

Figures 5 to 10, inclusive, show as ordinates the increase in strain under long continuation of a constant load for Series Nos. 3, 4, and 5. This increase in strain has been here termed "creep." The abscissas represent time in hours from the beginning of the test. All creep is considered as beginning immediately after the first application of a given load. Whenever the load was in-

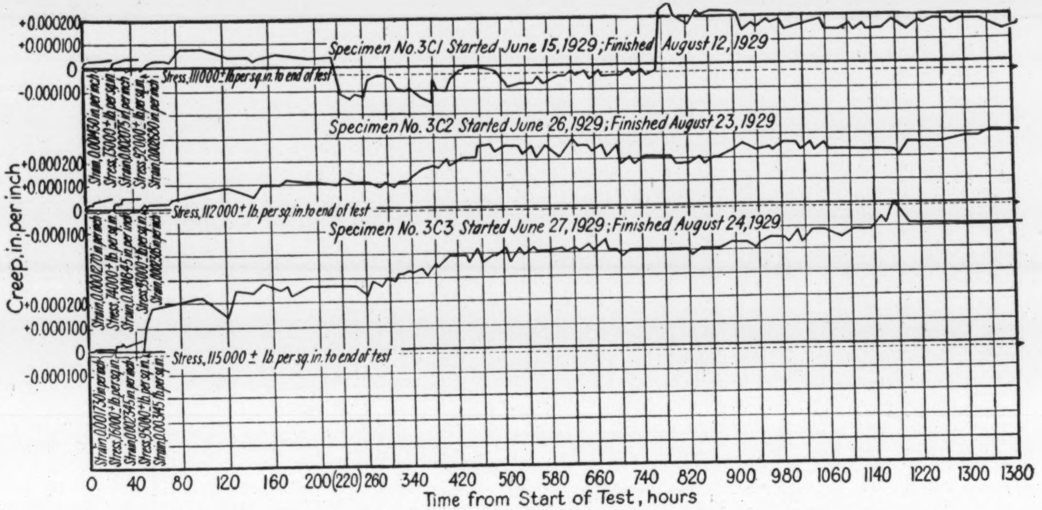


FIG. 6.—Creep Curves, Series No. 3C.

creased, the creep was considered as starting again at zero. The magnitude of any ordinate represents the cumulative effect of the continuation of load up to the time under consideration, and the slope of the curve represents the effect at the time under considera-

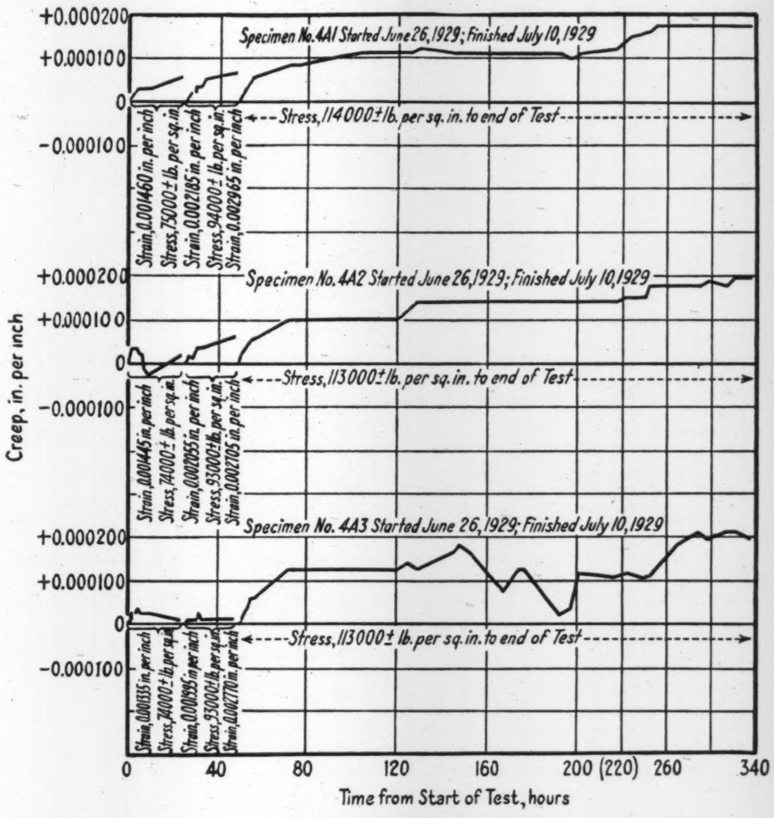


FIG. 7.—Creep Curves, Series No. 4*A*.

tion. For example, a large ordinate and a zero slope of the curve indicates that while there has been a large effect of the continuation of the load, that effect has ceased at least temporarily. The creep has been plotted to so large a scale that very small difference in strain may cause a change in slope. However, there are some irregularities in the curves which were too great to be considered as falling within the range of permissible error. The cause of these irregularities has not been determined entirely satisfactorily, but there were indications that they may have been due to slight slipping at the points

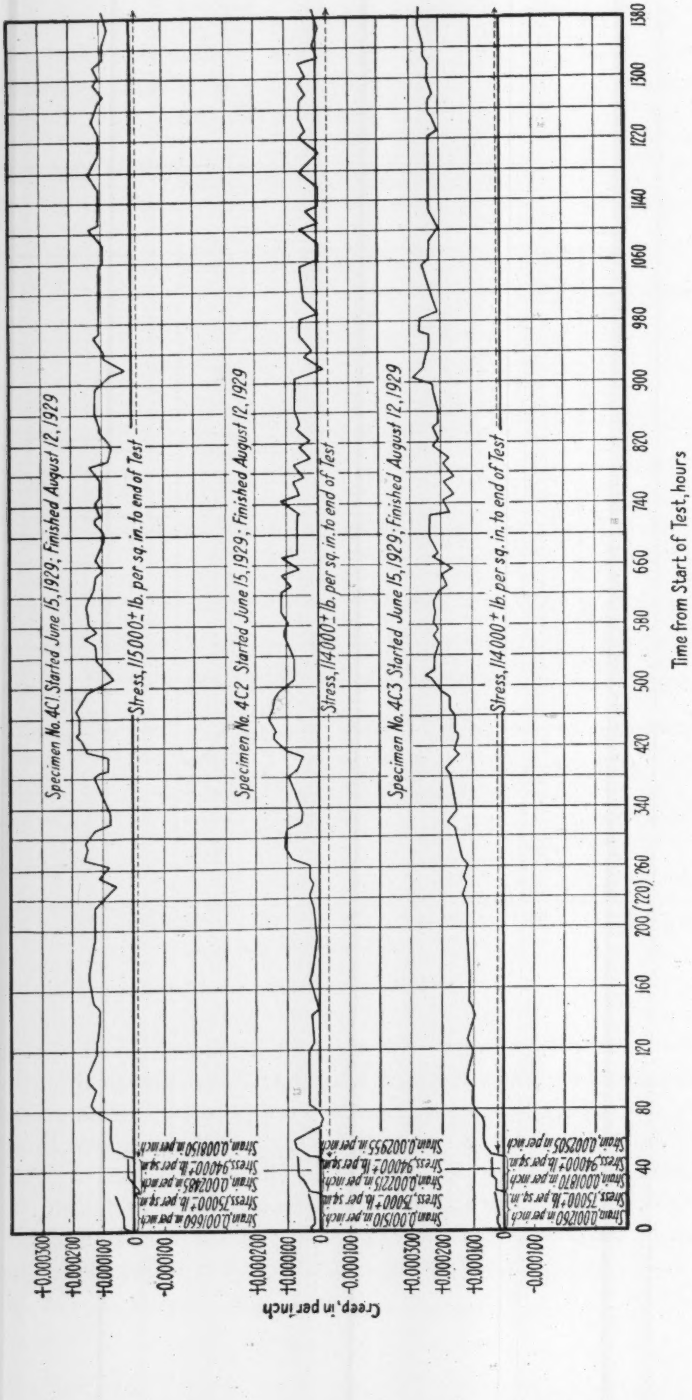


FIG. 8.—Creep Curves, Series No. 4C.

of attachment of the telemeters to the specimens. In the later tests the telemeters were tightened about every three days and most of the irregularities were eliminated. In interpreting the diagrams the general trend of the curves must be considered rather than the slope of the curve or the magnitude of ordinates at any particular point.

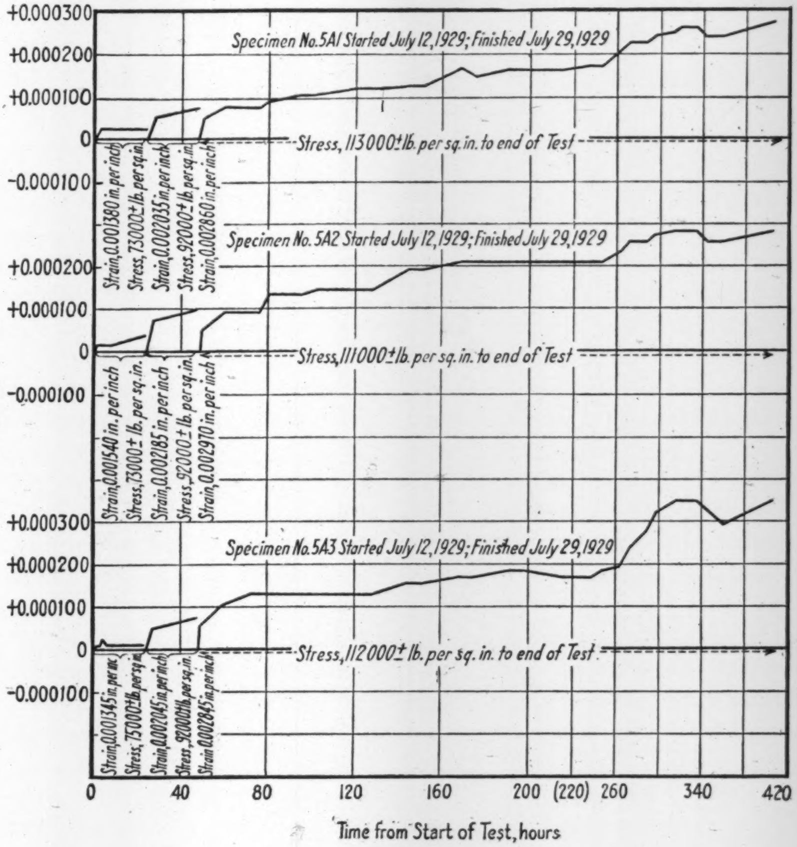


FIG. 9.—Creep Curves, Series No. 5*A*.

However, the general trend at points where these unexplained irregularities occurred means nothing and it seems that these portions of the curves must be eliminated from consideration.

In all the specimens tested under long-continued load a stress of approximately 74,000 lb. per sq. in. was applied for one day, the load was then increased to approximately 93,000 lb. per sq. in. and held for one day. It was then increased to approximately 113,000 lb. per

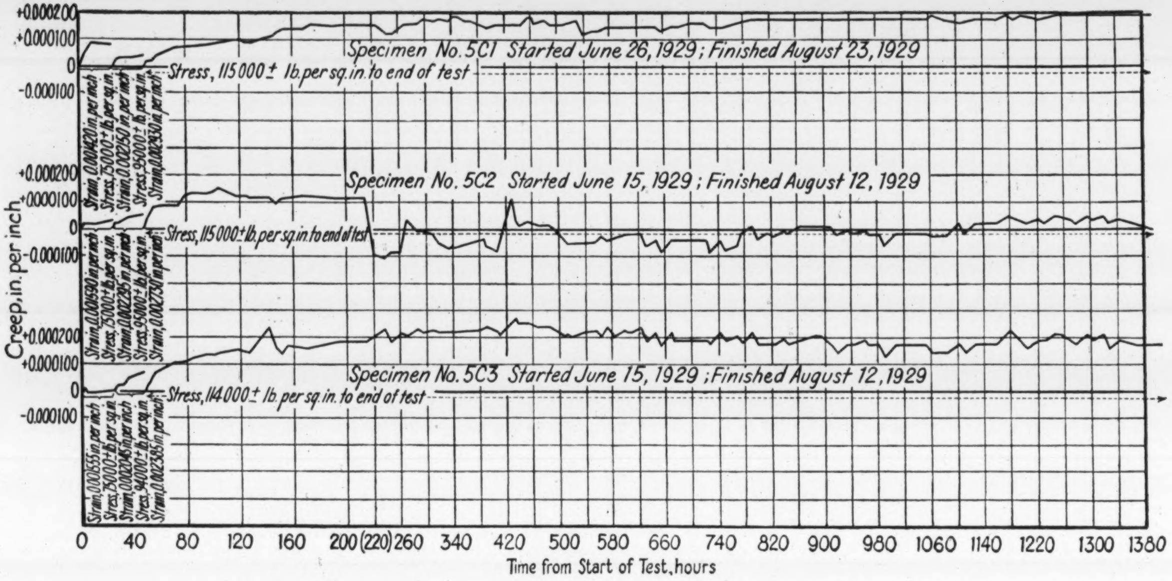


FIG. 10.—Creep Curves, Series No. 5C.

sq. in. and held for two weeks in Series Nos. 3*A*, 4*A*, and 5*A*, and for two months in Series No. 3*C*, 4*C*, and 5*C*.

As mentioned under rate of creep, Series No. 3*A*, the stresses for the test loads are given as 76,000, 95,000 and 114,000 lb. per sq. in. These were the stresses intended. Owing, however, to the variation in the ratio of the length of the long arm of the loading lever to that of the short arm, due to the fact that the knife edges were not in the same plane, difficulty was experienced in securing exactly the desired load. The values here given are the averages of the loads applied. The actual values are given in Figs. 5 to 10.

In Series 3*A* the wires were suspended straight from clamps. For this series, as shown in Fig. 5, there was no creep with any of the three specimens for the first 8 hours under the stress of 74,000 lb. per sq. in. During the remaining 16 hours specimens 3*A*2 and 3*A*3 showed creeps of about 0.000025 and 0.000055 in., respectively, while specimen 3*A*1 showed no creep at all under this load. Under the stress of 93,000 lb. per sq. in., the total creep in the 24 hours of the test was 0.000045, 0.000100, and 0.000055 in. per inch, for specimens 3*A*1, 3*A*2, and 3*A*3, respectively. With the 2-weeks' test under 113,000 lb. per sq. in., the creep started at a fairly rapid rate, gradually slowing down but showing a continued increase throughout the 2 weeks and giving an average total creep at the end of the period of 0.000220 in. per inch. This final creep is largely influenced by a marked decrease in creep for specimen 3*A*3 in the last 40 hours of the 2-weeks' period. Except for this decrease the average creep would be 0.000280 in. per inch.

In Series No. 4*A* the wires were placed around the sheave in the direction of the natural coiling curve. The creep for this series is shown in Fig. 7. There are irregularities in the curves for specimens 4*A*2 and 4*A*3. For specimen 4*A*2 under the stress of 74,000 lb. per sq. in. the creep decreased after 2 hours under load for about the next 8 hours and then increased again. For specimen 4*A*3 the creep curve was very irregular under the stress of 113,000 lb. per sq. in. from 120 to 200 hours. With these exceptions, the general trend indicates a sharp increase in creep for about the first four hours, after which there was nearly a constant rate of increase in the creep for the remainder of the 24-hour periods under stresses of 74,000 and 93,000 lb. per sq. in., respectively. Likewise, with the load of approximately 113,000 lb. per sq. in. there was a sharp increase in creep for about the first 24 hours followed by a much less rapid rate of increase in creep throughout the remainder of the 2-weeks' period. The general shape of the curves indicates that creep had not ceased at the end of the 2-weeks' tests.

In Series No. 5*A* the specimens were placed around the sheave with the curvature opposite to the direction of the natural coiling curve. In placing the wires there was a tendency for them to readjust themselves into the natural coiling curves, but extreme care was taken and it is believed that as tested, the wires were bent in the reverse direction. The creep for this series is shown in Fig. 9. The curves for creep are similar to those for Series No. 4*A* (placed around the sheave with their curvature in the direction of the natural coiling curve) except that the slopes everywhere were greater than those for Series 4*A*. This indicates that the rate of increase of creep was greater than for Series No. 4*A*. Also the total amount of creep was greater. In Series No. 5*A* the average total creep for the three specimens at the end of the 2-weeks' period was 0.000300 in. per inch, whereas in Series No. 4*A* it was only about 0.000180 in. per inch. In Series No. 4*A* the specimens were not held under load quite as long as those in Series No. 5*A*, but there is no indication that the creep in Series No. 4*A* would have reached the magnitude of that for Series No. 5*A* even if the duration of the two tests had been the same. It is even more evident in Series No. 5*A* than in Series No. 4*A* that creeping had not ceased at the end of the 2-weeks' period.

At about 266 hours (208 hours after the beginning of the 2-weeks' period) there appears in the cruves for all three groups, Series Nos. 3*A*, 4*A*, and 5*A*, a marked upward trend of the creep curve. While absent in some specimens, it is general enough to attract attention. It will be noted that the tests in the three groups were started at different times so that this upward trend cannot be ascribed to conditions existing in the laboratory. The change in horizontal scale at 260 hours accentuates the apparent rate of increase, but does not seem to be sufficient to explain it fully.

Figures 6, 8, and 10 give results of the creep measurements for Series Nos. 3*C*, 4*C*, and 5*C*. These figures were prepared in the same manner as Figs. 5, 7 and 9 for Series Nos. 3*A*, 4*A*, and 5*A*, except that for the stress of 113,000 lb. per sq. in. they give the creep over a 2-months' period instead of a 2-weeks' period. In general, the shape of the curves is similar to that of the curves for Series Nos. 3*A*, 4*A*, and 5*A*.

Although the figures for Series Nos. 3*A*, 3*C*, 4*A*, 4*C*, 5*A* and 5*C* indicate that creeping had not ceased at the end of the first 2 weeks of tests, the indication from Series Nos. 3*C*, 4*C* and 5*C* is that the amount of increase in creep after the end of 2 weeks was very small. By the end of 3 weeks the creeping may be said to have ceased. Omitting specimens 3*C*1, 4*C*1, 4*C*2, and 5*C*2 for which the creep curves were very irregular, the average creep at the end of 2 months was 0.000250 in. per inch.

Due to the irregularities previously noted it is difficult to make any reliable comparison of the rate of creep between Series Nos. 3, 4, and 5 in which the wires were tested straight, curved in the direction of coiling, and opposite to the direction of coiling, respectively. However, omitting specimens 4*A*3, 5*A*2, 3*C*1, 4*C*1, 4*C*2, and 5*C*2, averages of the curves for the remaining specimens were taken.

The averages for the 2-weeks' tests indicated that the largest creep occurred with the specimens which were bent around the sheave in the reverse direction of the coiling curve, the next largest with those tested straight, and the least with those bent in the direction of the coiling curve. The averages for the 2-months' tests indicated, on the other hand, that the largest creep occurred with those tested straight, the next largest with those bent in the direction of the natural coiling curve, and the least with those bent in the reverse direction. When the values for the 2-weeks' and the 2-months' tests were averaged, those tested straight showed somewhat the largest creep, and there was no large difference between those bent in the natural direction of the coiling curve and those bent in the reverse direction. The average creep was 0.000280, 0.000215 and 0.000224 in. per inch for the specimens tested straight, bent in the natural direction, and in the reverse direction of the coiling curve, respectively. With this difference in the results for the 2-weeks' and the 2-months' tests, it seems fair to conclude that there was little differ-

TABLE VI.—MODULUS OF ELASTICITY TESTS FOR SPECIMENS FROM SERIES NOS. 3*A*, 4*A*, AND 5*A*.

Specimen		Diameter, in.	Proportional Limit, lb. per sq. in.	Stress at 0.75 per cent Elongation, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 8 in., per cent	Reduction of Area, per cent	Modulus of Elasticity, lb. per sq. in.
Laboratory Number	Field Number							
3*A*1	72W121	0.195	110 000	175 500	219 100	5.0	1.0[b]	28 000 000
3*A*2	72W121	0.195	115 000	178 000	226 400	3.7	19.4	27 400 000
3*A*3	72W121	0.195	110 000	174 500	222 400	6.2	21.3	27 000 000
Average			113 300	176 000	224 900	5.0	20.4	27 460 000
4*A*1	72W122	0.194	100 000	168 000	229 700	4.4	24.0	24 800 000[b]
4*A*1[a]	72W122	0.194	90 000	163 000	229 900	4.3	17.6	26 600 000
4*A*2	72W122	0.195	80 000	173 000	231 400	5.0	20.3	26 400 000
4*A*3	72W122	0.195	100 000	179 000	225 900	3.7	22.3	28 000 000
Average			92 500	171 000	229 200	4.4	21.0	27 000 000
5*A*1	72W123	0.195	110 000	180 000	225 400	6.2	15.7	29 400 000
5*A*2	72W123	0.195	120 000	184 000	232 900	4.4	17.6	27 300 000
5*A*3	72W123	0.194	110 000	179 000	228 500	5.6	14.9	28 000 000
Average			110 000	181 000	228 900	5.4	16.1	28 230 000

[a] Second test on another sample from Series 4*A*.
[b] Not averaged in group.

ence, so far as creep is concerned, between the straight specimens and those bent in either direction.

The modulus of elasticity, proportional limit and other properties, determined on coupons from the specimens which had previously been subjected to long-time loading stress, are given in Table VI.

STRESS-STRAIN RATIOS

Since a part of the strain measured in the long-time tests is a creep, it cannot be called an elastic strain and the stress-strain ratio will therefore not be a true modulus of elasticity. However, the determinations of the stress-strain ratio with the telemeters afford a basis for judging the correctness of the telemeter strain readings and for this purpose are recorded in Table VII for certain specimens of Series Nos. 3, 4, and 5. For comparison the values of modulus of elasticity determined by the Ewing extensometer on the same specimens are shown in the last column of this table.

TABLE VII.—COMPARISON OF STRESS-STRAIN RATIOS FROM LONG-TIME TESTS WITH MODULUS OF ELASTICITY.

Specimen	Stress-Strain Ratio from 2-Weeks' Tests						Modulus of Elasticity from Table VI, lb. per sq. in.
	74 000 lb. per sq. in. Stress		93 000 lb. per sq. in. Stress		113 000 lb. per sq. in. Stress		
	Beginning	End	Beginning	End	Beginning	End	
No. 3*A*1	28 118 000	28 286 000	28 213 000	27 696 000	27 704 000	26 260 000	28 000 000
No. 3*A*2	30 942 000	29 790 000	30 739 000	29 286 000	30 736 000	28 097 000	27 400 000
No. 3*A*3	31 873 000	31 346 000	30 123 000	29 360 000	30 485 000	25 910 000	27 000 000
No. 4*A*1	28 849 000	27 953 000	28 288 000	27 502 000	27 555 000	26 127 000	25 700 000
No. 4*A*2	30 138 000	29 768 000	30 628 000	29 825 000	30 640 000	28 634 000	26 400 000
No. 4*A*3	32 180 000	31 985 000	31 253 000	31 152 000	29 625 000	27 777 000	28 000 000
No. 5*A*1	30 033 000	29 527 000	29 864 000	28 802 000	28 066 000	26 050 000	29 400 000
No. 5*A*2	27 792 000	27 127 000	28 325 000	27 107 000	27 370 000	24 967 000	27 300 000
No. 5*A*3	31 390 000	31 225 000	30 005 000	28 967 000	28 446 000	25 421 000	28 000 000

The average of these values is 27,440,000 lb. per sq. in. and the average for Series Nos. 1 and 2 is 27,900,000 lb. per sq. in. Stress-strain ratios computed from stress which included creep should be less than these values. However, the stress-strain ratios were generally greater than 28,000,000 lb. per sq. in., indicating slight error somewhere, probably in the telemeters. The stress-strain ratio in Table VII generally decreased as the stress increased. This should be expected if the measured strains included creep. Especially should this be true for the stress of 113,000 lb. per sq. in., since the proportional limit as shown by Series Nos. 1 and 2 was generally about 100,000 to 110,000 lb. per sq. in.

EFFECT OF LONG-CONTINUED LOADING ON TENSILE STRENGTH

The effect of the long-continued load on the tensile strength has been summarized in Table VIII. In column 3 the strengths are given for specimens tested straight and continuously to failure without previously having been subjected to any long-time test. In columns 4 and 5 are given the strengths of specimens tested in the same manner after they had been loaded for 2 weeks and 2 months, respectively, with loads causing a stress of approximately 113,000 lb. per sq. in. The specimen number indicates the series and the coil number. For example, the value in column 5 for Series No. 3, coil 2 gives the result for the test of specimen 3*C*2. Likewise the value in column 3 for Series No. 3, coil 2, gives the average strength for specimens 3*B*2 and 3*B*2.1.

TABLE VIII.—EFFECT OF LONG-TIME LOADING ON TENSILE STRENGTH—SUMMARY OF RESULTS FOR SERIES NOS. 3, 4, AND 5.

(All values except as indicated are results of single tests.)

Series	Coil	Strength, lb. per sq. in.			Reduction in Strength, per cent	
		Short-time Tests Tested Directly to Failure[a]	Tested After Being Loaded for 2 Weeks[d]	Tested After Being Loaded for 2 Months[e]	By Loading for 2 Weeks Before Testing	By Loading for 2 Months Before Testing
1	2	3	4	5	6	7
No. 3..	No. 1....	224 600[b]	221 400	224 700	+1.42	−0.045
	No. 2....	229 900[b]	226 400	229 400	+1.52	+0.22
	No. 3....	225 000[b]	227 000	226 300	−0.89	−0.58
No. 4..	No. 1....	219 200	228 000	227 000	−4.02	−3.56
	No. 2....	229 700	234 300	234 400	−2.00	−2.05
	No. 3....	226 400	229 400	231 000	−1.33	−2.03
No. 5..	No. 1....	220 700	224 700	222 200	−1.81	−0.68
	No. 2....	229 200	231 300	233 800	−0.92	−2.01
	No. 3....	225 400	226 900	229 300	−0.67	−1.73
No. 8..	No. 1....	224 400[c]	......	......	......	......
	No. 2....	230 900[c]	......	......	......	......
	No. 3....	227 500[c]	......	......	......	......

[a] The values in this column are those referred to in the text as Series Nos. 3*B*, 4*B*, etc.

[b] Average of two specimens.

[c] Averages for coils Nos. 1, 2, and 3.

[d] The values in this column are those referred to in the text as Series Nos. 3*C*, 4*C*, etc.

[e] The values in this column are those referred to in the text as Series Nos. 3*A*, 4*A*, etc.

A good degree of uniformity in tests of the same kind on individual specimens from the three coils is shown in Table VIII. Also, there is little difference in the average strength for the different cases. The extreme range between group averages is about 2.5 per cent of the mean of the highest and lowest averages. The differences in strength are in general too small to represent effect of differences in treatment, and it may be concluded that the tensile strength was not affected by the duration of the test or by testing the wires around a sheave either in the direction of the coiling curve or in the reverse direction. The average strengths for coils Nos. 1, 2, and 3, obtained in Series No. 8, uniformity tests, are repeated under Series No. 3, column 3, in this table for comparison. These values could have been used as well as those obtained from Series No. 3 in the above comparison without any change in the conclusions.

Tests were made for the purpose of determining the loss of strength in wire that has suffered mishandling, Series No. 6. Each test was parallel with the straight tension test for ultimate strength only. Wires were placed over a sheave 19½ in. in diameter in a testing machine and tested directly to failure.

In Series No. 6*A*, one wire from each of three coils as placed on the sheave was bent in the direction of its original coiling curve.

In Series No. 6*B*, one wire from each of three coils as placed on the sheave was bent in a direction opposite to that of its natural coiling curve.

In Series No. 6*C*, one wire from each of three coils was closed up on a 5-in. radius, then straightened and tested directly to failure around the sheave.

In Series No. 6*D*, one wire from each of three coils was closed up on a 5-in. radius, straightened, closed in the opposite direction to a 5-in. radius, straightened again, and tested directly to failure around the sheave.

In Series No. 6*E*, one wire from each of three coils was dented on the convex side of the curve, and then tested directly to failure around the sheave.

In Series No. 6*F*, one wire from each of three coils was dented at the tangent point, on the convex side of the curve, and then tested directly to failure around the sheave.

In Series No. 6*G*, one wire from each of three coils was dented on the straight portion and tested directly to failure around the sheave.

In Series Nos. 6*E*, 6*F* and 6*G*, the indentation was intended not to exceed what might happen to a wire in the process of fabrication by coming in rather violent contact with a square edge of structural steel.

In Series No. 6*H*, three wires from each of three coils were pre-shaped, by pulling vigorously around a sheave 4 ft. in diameter and releasing, this being somewhat more severe treatment than the wire receives while being shuttled back and forth across the bridge on a spider 4 ft. in diameter. Two of the three wires (Series No. 6*Ha*) were then tested directly to failure around the sheave, and one of them (Series No. 6*Hb*) was tested straight.

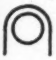
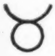
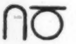
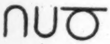
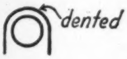
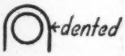
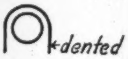
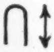
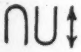
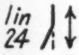
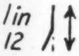
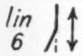
The wires in Series Nos. 6*J* to 6*N* were not tested around a sheave but were tested straight in tension between two clamps.

In Series No. 6*J*, one wire from each of three coils was closed up on a 5-in. radius, straightened, and tested directly to failure in straight tension.

In Series No. 6*K*, one wire from each of three coils was closed up on a 5-in. radius, straightened, closed on a 5-in. radius in the opposite direction, straightened, and tested directly to failure in straight tension.

In Series No. 6*L*, one wire from each of three coils was kinked at an angle of ½ in. in 12 in. (approximately 2.4 deg.), then straightened and pulled directly to failure.

TABLE IX.—EFFECT OF ABUSE ON TENSILE STRENGTH OF WIRE—SUMMARY OF RESULTS FROM SERIES NO. 6.

Specimen	Method of Test	Strength of Wire, lb. per sq. in.			Reduction in Strength, per cent[a]			Average
		Coil No. 1	Coil No. 2	Coil No. 3	Coil No. 1	Coil No. 2	Coil No. 3	
Normal Strength Average.................		224 400	230 900	227 500				
6*A*		221 700	229 200	222 400	+1.20	+0.74	+2.24	+1.39
6*B*		221 600	229 200	225 700	+1.25	+0.74	+0.79	+0.93
6*C*		222 600	227 200	225 700	+0.80	+1.60	+0.79	+1.06
6*D*		221 400	226 200	227 000	+1.34	+2.04	+0.22	+1.20
6*E*		221 700	229 700	226 000	+1.20	+0.52	+0.66	+0.79
6*F*		223 200	225 500	225 000	+0.54	+2.34	+1.10	+1.33
6*G*		215 900	225 900	216 300	+3.79	+2.17	+4.92	+3.63
6*Ha*	[b]	225 500	231 900	227 800	−0.49	−0.43	−0.13	−0.35
6*Hb*	[b]	223 700	229 700	226 700	+0.31	+0.52	+0.35	+0.39
6*J*		223 400	231 400	226 700	+0.45	−0.21	+0.35	+0.20
6*K*		221 700	231 000	224 400	+1.20	−0.42	+1.36	+0.71
6*L*		223 000	233 400	226 000	+0.62	−1.08	+0.66	+0.07
6*M*		222 700	231 700	226 000	+0.76	−0.34	+0.66	+0.36
6*N*		222 700	230 400	227 000	+0.76	+0.21	+0.22	+0.39

[a] In these columns − indicates increase in strength of wire, + indicates decrease in strength of wire.

[b] See enumeration in section on Effect of Long-Continued Loading on Tensile Strength, see pp 334 and 336.

NOTES.—For significance of symbols see enumeration in section on Effect of Long-Continued Loading on Tensile Strength, see pp. 334 and 336.

In Series No. 6*M*, one wire from each of three coils was kinked at an angle in 12 in. (approximately 4.8 deg.).

In Series No. 6*N*, one wire from each of three coils was kinked at an angle of 2 in. in 12 in. (approximately 9.5 deg.).

The effect of mishandling wires on their strength is shown in Table IX. The greatest reduction in strength, 3.6 per cent, was found in Series No. 6*G*. This was the wire which was dented on the straight portion. A detailed photograph of the dented wire is shown in Fig. 11. In all other cases the reduction in strength was less than 1.5 per cent and this amount was so small that it cannot with certainty be attributed to the mishandling. It may be concluded that the mishandling had no effect on the strength of the wire with the exception of Series No. 6*G*. The fact that indentation on other portions of the wire showed no appreciable effect might indicate that the effect shown in results of this series was more or less accidental.

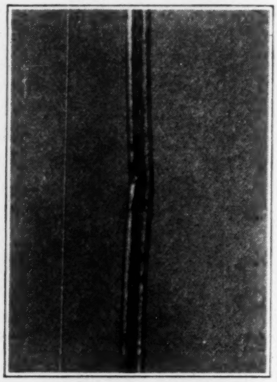


FIG. 11.—Dented Wire, Series No. 6.

EFFECT OF LOW TEMPERATURE ON TENSILE STRENGTH

To determine the effect of low temperature on the strength of the wire, Series No. 7, wires were subjected to contact with dry ice (congealed carbonic acid gas) during the process of testing. Two specimens from each coil were tested straight and two were tested around the sheave. The dry ice was held in contact with the wire from 40 to 60 minutes before testing. Thermometer readings indicated the temperature of the dry ice to range from -67 to $-103°$ F. The results of the tests show for these specimens an average reduction of tensile strength of 0.56 per cent. All wires broke outside of the box of dry ice and the reduction in strength shown must, therefore, be accidental and cannot be attributed to the effect of the low temperature.

EFFECT OF SEATING CONDITIONS OF WIRES ON TENSILE STRENGTH

Tests were made to study the seating and wedging action of wires laid over strand shoes. Two wires were placed around the sheave in a groove in rectangular cross-section just wide enough to take the two wires side by side without appreciable clearance. These wires carried no load, and are termed "dead wires." A third wire was placed around the sheave bearing equally on the two dead wires. It had a bearing through 180 deg. of the sheave and the straight portion left the sheaves parallel to each other. In Series No. 10 the live wire bore equally on the two dead wires all the way around the semicircular sheave. In Series No. 11 the live wire was wedged against the wall at one side of the groove for part of the distance and then forced over to the opposite side by means of another wedge. The live wire was tested to failure distributing the load as nearly equally as possible between the two tangents.

TABLE X.—EFFECT OF SEATING CONDITIONS ON STRENGTH OF WIRE.

	Specimen	Strength of Wire, lb. per sq. in.			Reduction in Strength, per cent [a]			
		Coil No .1	Coil No. 2	Coil No. 3	Coil No. 1	Coil No. 2	Coil No. 3	Average
SERIES No. 10, WEDGING ACTION								
Normal Strength....	....	224 400	230 900	227 500				
Live Wires.......	No. 10*A*........	224 200	230 400	225 700	+0.13	+0.04	−0.62	−0.15
	No. 10*B*........	224 900	232 600	226 400				
	No. 10*C*........	225 000	230 200	226 200				
	Average......	224 700	231 000	226 100				
Dead Wires.......	No. 10*A*........	221 400	230 700	221 700	−1.20	−0.26	−1.45	−0.97
	No. 10*B*........	221 700	231 800	226 400				
	No. 10*C*........	222 000	228 400	224 400				
	Average......	221 700	230 300	224 200				
SERIES No. 11, CROSSING OF WIRES								
Normal Strength....	....	224 400	230 900	227 500				
Live Wires........	No. 11*A*........	228 700	229 700	227 600	+0.31	−0.39	−0.26	−0.11
	No. 11*B*........	224 700	230 200	227 000				
	No. 11*C*........	222 000	230 200	226 000				
	Average......	225 100	230 000	226 900				
Dead Wires.......	No. 11*A*........	224 000	232 100	226 700	−0.36	−0.13	−0.80	−0.43
	No. 11*B*........	223 000	230 400	226 000				
	No. 11*C*........	223 700	229 700	224 200				
	Average......	223 600	230 600	225 700				

[a] In these columns + indicates increase in strength of wire, — indicates decrease in strength of wire.

The results of tests for both series are given in Table X. The largest reduction in strength for the live wire was 0.62 per cent, and the largest for the dead wires was 1.45 per cent. These reductions are so slight as to warrant the statement that the effect of variation in seating conditions on strengths of the wire was negligible.

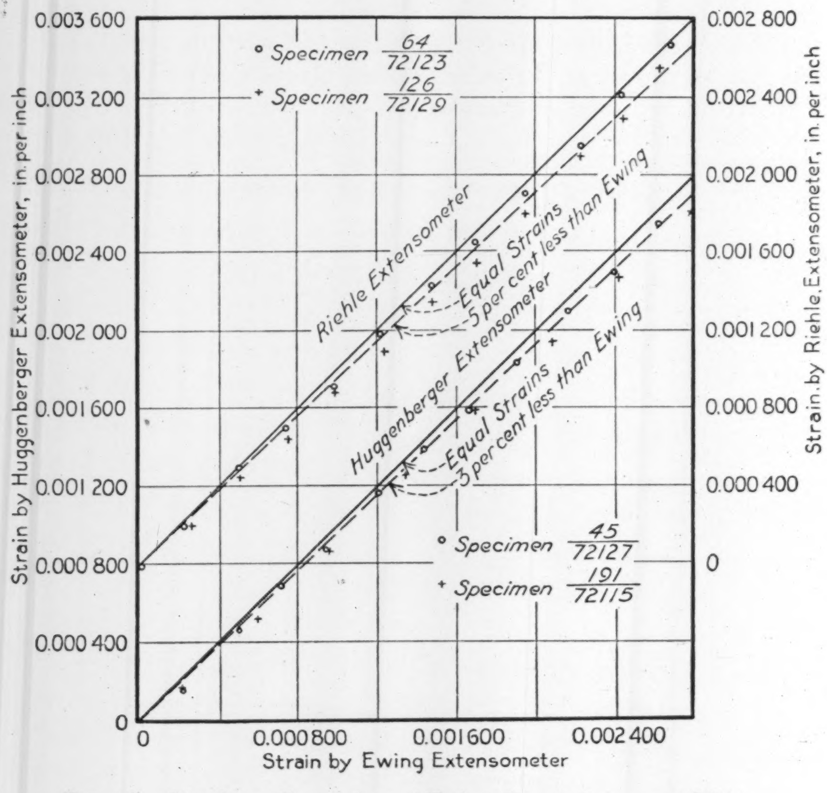


FIG. 12.—Showing a Comparison of Ewing, Huggenberger and Riehle Extensometers.

MODULUS OF ELASTICITY

Five coupons of cold-drawn wire clipped from the ends of specimens tested for modulus of elasticity at the Roebling Plant in Trenton, were received at Fritz Engineering Laboratory for a check determination of the modulus. They were tested in a 50,000-lb., 2-screw Riehle testing machine. The strains were measured in all five coupons with a Ewing extensometer over an 8-in. gage length. A Huggenberger extensometer was used also with a gage length of 1 in. on two of the

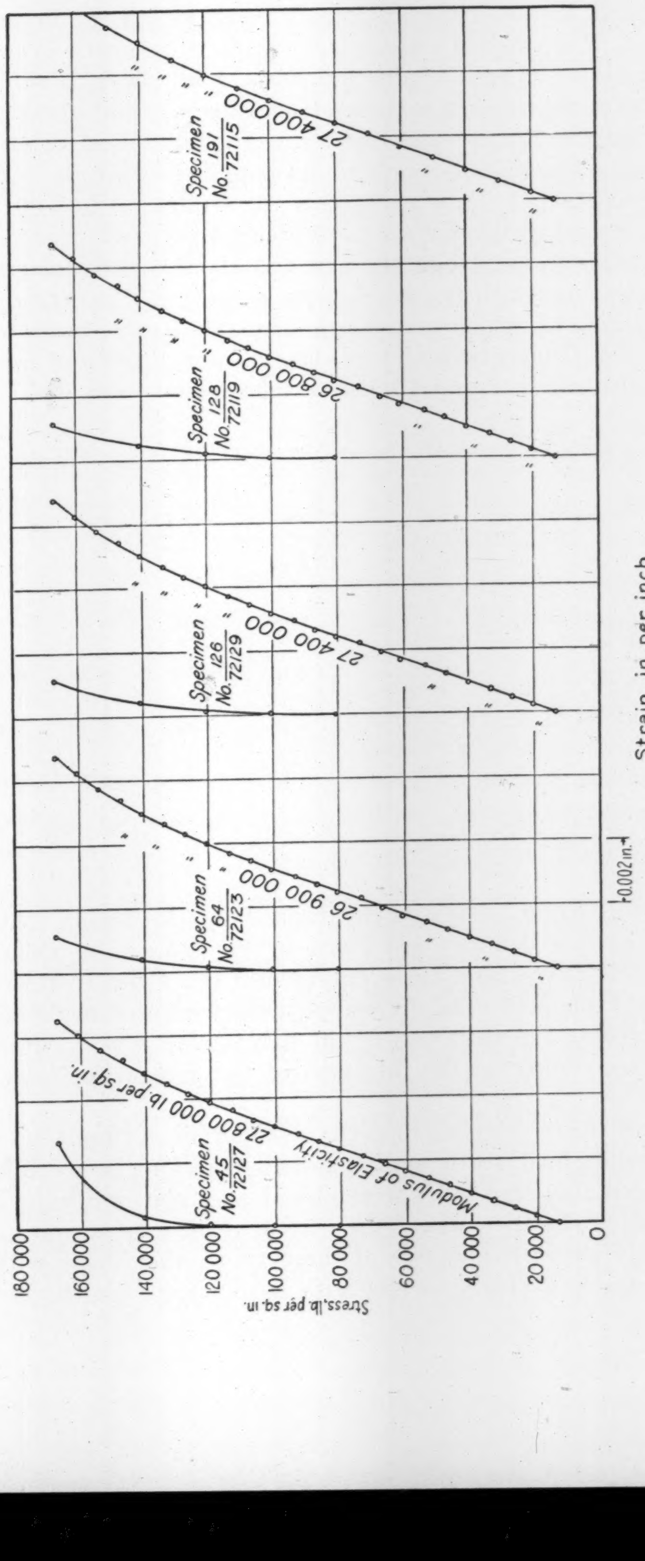


FIG. 13.—Stress-Strain and Set Curves for Coupons from Roebling Specimens.

specimens and a Riehle extensometer with a gage length of 2 in. on the other three. The smallest difference in readings recorded in taking the data corresponds to a strain of 0.0000125 in. per inch with the Ewing, 0.000028 in. per inch with the Huggenberger, and 0.000025 in. per inch with the Riehle extensometer. An initial load of 400 lb. (approximately 13,000 lb. per sq. in.) was applied before the reading of strains was started. The average of the strains up to 0.0028 in. per inch measured with the Ewing was about 3 per cent greater than that measured with the Huggenberger, and about 5 per cent greater than that measured with the Riehle extensometer. The comparison is shown in Fig. 12, which gives results for two specimens in which the Ewing and Huggenberger extensometers were used and for two others in which the Ewing and Riehle extensometers were used.

TABLE XI.—RESULT OF TESTS ON COUPONS FROM ROEBLING SPECIMENS.

Specimen	Diameter, in.	Proportional Limit, lb. per sq. in.	Maximum Stress, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.
$\frac{45}{72127}$	0.195	113 800	227 000	27 800 000
$\frac{64}{72123}$	0.195	120 500	224 700	26 900 000
$\frac{126}{72129}$	0.195	107 100	220 300	27 400 000
$\frac{128}{72119}$	0.195	107 100	227 700	26 800 000
$\frac{191}{72115}$	0.196	105 400	229 000	27 400 000
Average		110 780	225 740	27 260 000

The stress-strain curves as determined by the Ewing extensometer for the five coupons are given in Fig. 13. The values of modulus of elasticity from these curves and the ultimate strengths are given in Table XI. The diameters of the wire used in the determinations include the thickness of the galvanizing coat. After the tests had been completed the thickness of the galvanizing coat was measured.

To check the modulus of elasticity as determined from tests with a testing machine load, a wire approximately 22 ft. long from coil No. 2 was suspended and dead loads were placed on a platform hung from the lower end of the 22-ft. wire. Elongation of the wire was measured independently by extensometers of three types, the Ewing with an 8-in. gage length, a Huggenberger with a 1-in. gage length, and by two Ames gages attached on opposite sides of the wire with a gage length of 8 ft. $\frac{1}{4}$ in. The load was applied in increments of 100 lb. up to a total of 2630 and 2480 lb. in successive tests, giving stresses of 88,060 and 83,040 lb. per sq. in., respectively. The test to 2630 lb. with increasing loads is designated as run No. 1 and with decreasing loads as run No. 2. The test to 2480 lb. with increasing loads is designated as run No. 3, and with decreasing loads as run No. 4. The stress-strain curves for the four runs using the Ames gages are shown in Fig. 14. The agreement between the different extensometers is shown by comparing the moduli in Table XII.

After the dead-load tests described above were completed, a short piece was cut from the 22-ft. length and four determinations for modulus of elasticity were made in a 50,000-lb. testing machine using a Ewing extensometer. The stress-strain curves are given in Fig. 14 and the moduli in Table XII.

TABLE XII.—RESULTS OF DEAD-LOAD TESTS—MODULUS OF ELASTICITY.

Run	Modulus of Elasticity, lb. per sq. in.			
	Ewing Extensometer	Ames Extensometer	Huggenberger Extensometer	Short Specimen from 22-ft. Length, Ewing Extensometer
No. 1[a]	29 250 000	28 400 000	....	29 000 000
No. 2[b]	28 450 000	28 350 000	29 050 000	29 000 000
No. 3[a]	28 000 000	28 400 000	27 650 000	28 300 000
No. 4[b]	28 650 000	28 200 000	28 900 000	28 000 000
Average	28 590 000	28 340 000	28 530 000	28 570 000
Grand Average	28 508 000			

[a] With increasing loads.
[b] With decreasing loads.

A special effort was made to secure accuracy in the determination of modulus of elasticity in the tests of the coupons from the Roebling Co. and in the dead-load tests, as it was understood that the values so determined where to be used as a basis for computing the deflections of the bridge. The average modulus of elasticity for the former as given in Table XI, is 27,260,000 lb. per sq. in. and that for the latter as given in Table XII is 28,590,000 lb. per sq. in. The average modulus of elasticity determined on coupons from the dead-load test specimens is 28,570,000 lb. per sq. in. All these were deterined with the Ewing extensometer and it is believed that more weight should be given to them than to the other values. The grand average for these three average values is 28,120,000 lb. per sq. in.

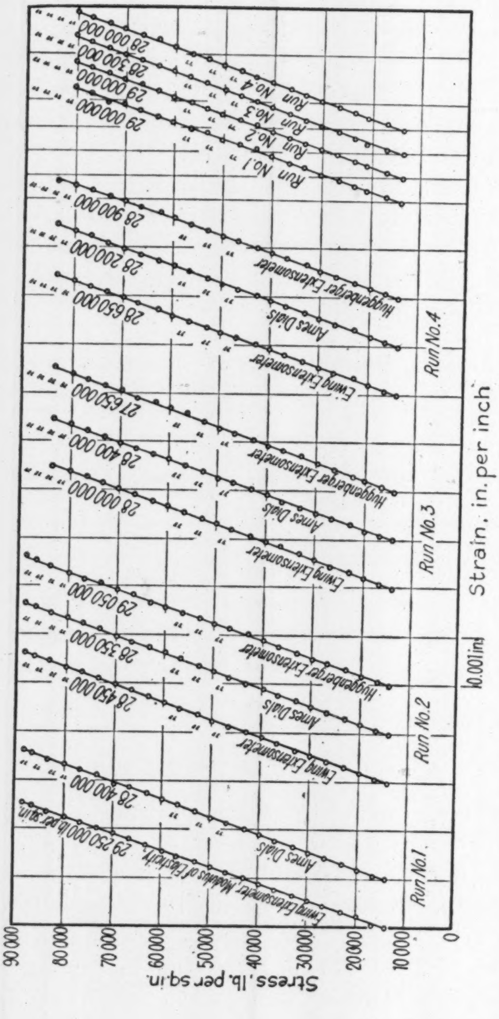


FIG. 14.—Stress-Strain Curves for Dead-Load Tests.

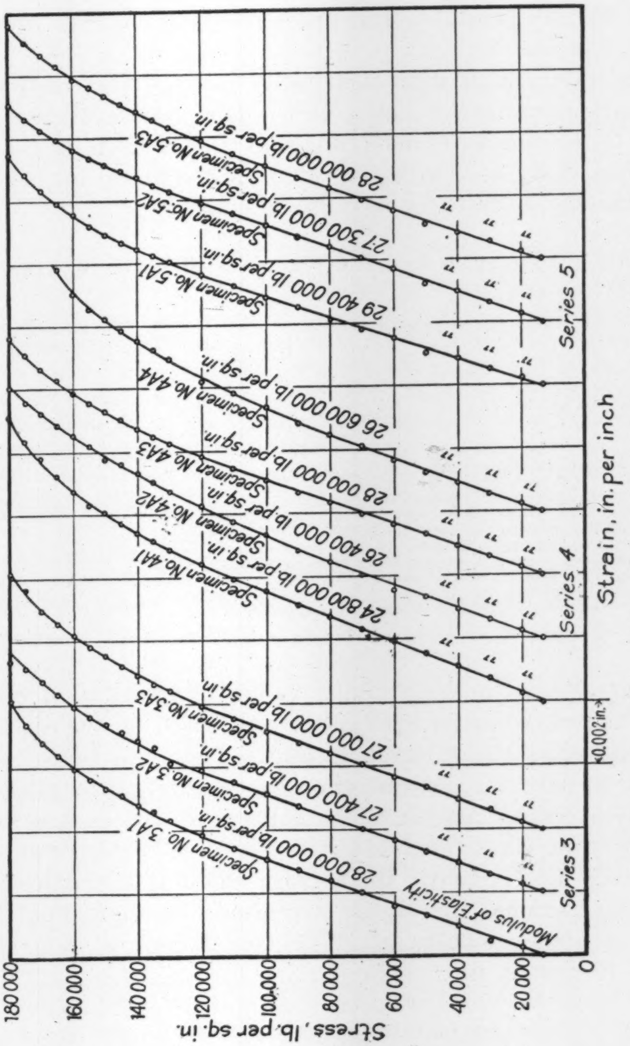


FIG. 15.—Stress-Strain Curves from Tension Tests of Detroit Bridge Wire, Series Nos. 3, 4 and 5.

Other tests were made for modulus on all specimens of Series Nos. 1 and 2 and on certain specimens of Series Nos. 3, 4, and 5 which had previously been subjected to long-time loads. The Ewing extensometer was used in all the tests. These values are reported in Tables III, IV, and VI, and the stress-strain curves are shown in Figs. 2, 3, 4, and 15.

All the values of modulus of elasticity as determined in this investigation are summarized in Table XIII. The grand average weighted according to the number of determinations is 27,855,000 lb. per sq. in., which agrees fairly well with the value of 28,120,000 lb. per sq. in. given by the special tests for modulus of elasticity.

TABLE XIII.—SUMMARY OF AVERAGE VALUES OF MODULUS OF ELASTICITY.

Description of Specimens	Number of Specimens	Number of Determinations	Modulus of Elasticity, lb. per sq. in.
Coupons from Roebling Co. Plant (Series No. 14)	5	5	27 260 000
22-ft. Specimen tested under dead load (Coil No. 2, Series No. 14)	1	4	28 590 000
Coupons from dead load specimen	1	4	28 570 000
Average	......	......	28 140 000
Specimens of Series No. 1—Acceptance tests	12	12	27 830 000
Specimens of Series No. 2—Acceptance tests	12	12	28 015 000
Specimens from Coil No. 1—Included in Series No. 2	2	2	27 750 000
Specimens from Coil No. 2—Included in Series No. 2	2	2	27 900 000
Specimens from Coil No. 3—Included in Series No. 2	2	2	27 000 000
Specimens which had been under long-time tests, averages for Coils Nos. 1, 2, and 3:			
(*a*) after 2 weeks straight tension, Series No. 3*A*	3	3	27 460 000
(*b*) after 2 weeks over sheave in direction of coiling curve, Series No. 4*A*	3	3	27 000 000
(*c*) after 2 weeks over sheave in reverse direction, Series No. 5 *A*	3	3	28 230 000
Grand average weighted according to the number of determinations			27 855 000

The areas used in determining values of modulus of elasticity noted in the preceeding paragraphs were all based on the diameter of the wire including the galvanizing coat. Determinations indicated a reduction of 0.003 in. in diameter on the removal of the galvanizing. Taking the average diameter of the galvanized wire at 0.195 in. the galvanizing coat constituted about 3 per cent of the area of the cross-section. Consequently the average modulus of elasticity based upon the net sectional area of the steel would be approximately 1.03 times the average modulus of 27,855,000 lb. per sq. in., that is, 28,690,000 lb. per sq. in.

EFFECT OF STORING WIRE IN COILS

To investigate the effect of the bending stresses developed by the coiling of the wire into coils to a diameter of 19½ in. during a prolonged time, ten wires 300 and 400 ft. long were wound into coils 19½ in. in diameter. The first coil was wound and stored on May 22 and the last one on June 25, 1929. Up to the present time (June, 1930) no breakage had occurred nor have any other visual effects been noted.

DEEP ETCHING AND METALLOGRAPHIC TESTS

Bradley Stoughton made a series of tests in the Department of Metallurgical Engineering at Lehigh University on metallographic examination and deep etching. Specimens from twelve different heats were examined.

The wires were split for examination for striations or fibrousness by means of etching and deep etching.

The results are given here in a condensed form:

Wires Nos. 72,121 and 72,122.—No serious segregation was discovered in either wire, and no striations or banded structure. The wires were first etched lightly with nitric acid. One wire showed a few white spots which may have been caused by a separation of iron carbide, due to too low a patenting temperature. This was not general nor sufficient enough to cause trouble. The second wire showed a few spots indicating slight segregation, but not sufficient to indicate defective material.

Both wires showed many inclusions under the microscope, some being large and some small. The chemical analysis confirmed the microscopic examination.

The structure under the microscope was good normal structure of cold-drawn and patented wire. The wires showed a normal decarbonization on the surface. The Rockwell hardness, "C" scale, averaged 42.5 and 43.0.

Wire No. 72,118.—The structure was uniform and normal except for slight excess of grain size. In one or two places in these samples were noted slight distortions of the grain structure, evidently produced during cold drawing. There were a few carbide particles to be seen. Deep surface seams were observed when the zinc coating was dissolved from the wire.

Wire No. 72,146.—Some carbide spots were observed and there was infrequent ferrite banding. No surface seams were found.

Wire No. 72W154.—With the exception of slight distortions in one or two places for grain structure, the wire was uniform under the light and deep etch. The number of inclusions was average. Several carbide particles were observed. The seams on the surface were slight.

Wire No. 42,123.—Decarbonization and inclusions were normal. There were some fairly deep surface seams. The average Rockwell hardness, "C" scale, was 45. Uniform structure under deep etch test.

Wire No. 72,125.—Good structure, fairly free from striations. Decarbonization was normal with fewer inclusions. There was one fairly bad surface seam at one end of the coil. The average Rockwell hardness, "C" scale, was 43. Uniform structure under deep etch. Two carbide spots were found.

Wire No. 72W130.—The structure was slightly coarser with some striations. A single carbide was found. Decarbonization was normal. There were fewer inclusions. A few fairly bad surface seams appeared. The average Rockwell hardness, "C" scale, was 44. It had a uniform structure under deep etch.

Wire No. 72W140.—The structure was somewhat coarse with many distinct ferrite striations. Decarbonization was normal. The steel is clean. There were no surface seams. The average Rockwell hardness, "C" scale, was 45. With a deep etch in hydrochloric acid at an elevated temperature, at no magnification, two distinct bands in the center of the specimen were seen black against a lighter background. A few carbide spots were noticeable.

Wire No. $\frac{30}{72W156}$.—Normal grain with striated structure and normal decarbonization. It was fairly clean, having one fairly bad seam at one end. The average Rockwell hardness, "C" scale, was 43. Deep etch test revealed a uniform structure.

Wire No. $\frac{137}{72W162}$.—Slight indication of striations while the grain and decarbonization were normal. The steel was clean, having one slight seam visible. The average Rockwell hardness, "C" scale, was 43. The deep etch test showed a decarbonization at one place. A few carbide spots were noticeable.

Wire No. $\frac{5}{72206}$.—The grain and decarbonization were normal. The steel was clean with no surface seams. A hot etch test showed down the center of the specimen a decided streak. The average Rockwell hardness, "C" scale, was 43.

CONCLUSIONS

The program of tests as planned and as described in this paper endeavors to cover all the practical information in which bridge engineers are interested as affecting the design, endurance and safety of bridges. While much knowledge and experience on bridge wire was on hand from past construction and behavior of numerous bridges, no systematic comprehensive series of tests was known heretofore. The tests presented before the Society were an attempt towards a more organized body of information. To the author's knowledge, such investigations as endurance or fatigue under dead weight for a long duration of time had not been made on bridge wire.

The results of the tests are highly satisfactory in all respects.

The wire along a coil was found to be as uniform as practical testing can indicate.

The limit of proportionality and the commencement of noticeable permanent set were found to be well above the design stresses of modern suspension bridges.

The continued load test developed no noticeable effect on the tensile strength of the specimen.

No wire broke in the covered portion on the sheave or at the point of tangency.

The phenomenon of creep shows satisfactory and interesting results. There was generally some creep within the period of the 24-hour tests under a load of 74,000 and 93,000 lb. per sq. in., but the amount, while small, varied so much that it is difficult to distinguish between creep and the errors in the readings. In the 2-weeks' tests under a load of 113,000 lb. per sq. in., the rate of creep was greater at the beginning of the test and gradually slowed down thereafter but it had not ceased at the end of the 2-weeks' period. The average creep within the 2 weeks for all conditions of tests was about 0.000230 in. per inch. In the 2-months' tests the increase in the amount of creep after 2 weeks was slight and after 3 weeks it had practically ceased. The average creep at the end of 2 months was 0.000240 in. per inch.

The engineer is generally interested in the effect of possible mishandling, kinking and notching of the wire during the various processes of stringing the cable. The tests have developed no noticeable effect on the ultimate strength of mishandled wire. The variation in the strength of the specimens subjected to varied kinds of abuse were generally not greater than the variation for the specimens in the uniformity series in which the wires were not subjected to abuse.

The metallurgical study showed the wire, as manufactured, to be of average commercial structure and uniform hardness. While the wire was not entirely free from inclusions and slags and showed not more than an average cleanliness, it was fully sufficient to meet the exactions imposed upon it by the tests.

DISCUSSION

Mr. H. C. Boynton.[1]—So far as the company with which I am identified is concerned, we corroborate practically all of the tests that have been made by Mr. Moisseiff and his associates. We are indeed indebted to Mr. Moisseiff and his associates for this very complete series of tests. Nearly all producers of bridge wire have at hand in their files similar series of tests, but these tests have not been made available for publication; consequently, I think we should sincerely congratulate Mr. Moisseiff for his frank discussion of the whole interesting subject of bridge wire.

Mr. T. C. Tweedie.[2]—I notice that Mr. Moisseiff states that he froze some of the wire between −66 and −113° F., and made a tension test on it. I should like to ask if any bending tests were made.

The reason I ask this question is because, by going over all the information I could get on the subject, I was very much struck with the point that the original heat-treated wire used in both the Detroit River bridge and the the Mount Hope bridge started to show failures at a time when the temperature in Detroit and in Rhode Island was at its lowest, and I wanted to know whether extreme cold has any effect on the resistance to bending stresses, especially in the heat-treated wire.

Mr. Bradley Stoughton.[3]—Referring to the tests made at Lehigh University, I want to say that we were instructed to make the most exhaustive tests and we did so. The importance of them perhaps is that we had also tested the heat-treated wire after it had failed, so that we had an opportunity to apply the same test to the cold-drawn wire which had been applied to the heat-treated wire, which proved to be unfit for the purpose. The U. S. Bureau of Standards is now studying that heat-treated wire, and I will not go into any lengthy discussion about it and its defects, but two things may be said: first, that it was a basic open-hearth wire, whereas the other wire is acid open-hearth wire. To the difference between acid and basic steel I attach a good deal of importance, some of the engineers of the Port of New York Authority to the contrary notwithstanding. The second point is that this first wire which failed had passed many satisfactory tests before it had been put into service. But, in being put into service, it was severely distorted and bent, which is a necessary consequence for spinning it into the bridge, and in that severe bending and distortion, the high tensile strength and high elastic limit which had been given to the wire by the heat treatment was "washed out of it," as *The Iron Age* expressed it, and I think very appropriately, so that it lost the properties on which the engineers depended for the support of the bridge. The structure of the cold-drawn wire was entirely different; the microscopic structure was radically different from that of the heat-treated wire. Likewise the deep etching test which Mr. Moisseiff mentioned that we made, showed a considerable difference in the two types of wire. The examination of the cold-drawn wire indicated that there was nothing in it that would not make it perfectly satisfactory for the work for which it was intended, and of course in that way merely corroborated the evidence of a great many years in which the type of wire had been used and spun into bridges without any untoward effects.

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[1] Metallurgist, John A. Roebling's Sons Co., Trenton, N. J.

[2] Metallurgist, Macwhyte Co., Kenosha, Wis.

[3] Professor in Charge, Department of Metallurgy, Lehigh University, Bethlehem, Pa.

MR. W. A. SLATER.[1]—Referring further to the tests made at Lehigh University, I am offering some information in answer to the question regarding the bending tests of the wire at low temperatures. Bending tests of the ordinary sort were not made, but we did test some of these wires around a sheave of the same diameter as the shoe used in the bridge, 19½ in., under low tempertures. It was not possible of course, to reproduce the temperatures that were to be met in practice without a more elaborate equipment than the mere use of dry ice, and the expense authorized for the investigation did not warrant us in providing that equipment. Therefore the wires were merely placed around the shoe and the temperature reduced by the application of dry ice and the test made under that condition. The temperatures secured ranged from -67 to $-103°$ F. The strength of these specimens averaged about ½ per cent lower than that of specimens tested in the usual manner, but as none of the breaks occurred in the portion whose temperature was reduced, it must be concluded that lowering the temperature did not reduce the strength.

MR. L. S. MOISSEIFF.[2]—As to the freezing test, I might add that as the trouble in the original heat-treated wire became apparent at a period of low temperature, the suggestion was made to test it by a freezing test. The original heat-treated wire which failed in the bridges was tested at that time. It was subjected to a freezing test to find whether the trouble was caused by low temperature. The result showed no effect of cold on the strength of the wire. In the new set of tests on cold-drawn wire, reported in the paper, the freezing test was included simply to amplify the scope of the entire testing program.

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[1] Research Professor of Engineering Materials, and Director, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa.

[2] Consulting Engineer, New York City.

THE EFFECT OF TEMPERATURE UPON THE TORSIONAL MODULUS OF SPRING MATERIALS

By F. P. Zimmerli,[1] W. P. Wood,[2] and G. D. Wilson[3]

Synopsis

The torsional moduli of several metals in wire section have been investigated over a temperature range extending from −100 to +800° F. (−75 to +425° C.). These values have been determined on account of the increasing use of metals in torsion at temperatures other than atmospheric. The valve springs in aircraft engines furnish an example of this.

This investigation was carried out by applying simple torsion to wire sections in a specially constructed furnace. Having determined the angle of twist for various loads, the modulus was calculated by inversion of the usual expression representing the relation between the twisting moment and the resultant angle of twist in a member subjected to pure torsion.

The important results may be summarized as follows:

1. There is a general downward trend in the moduli as temperature increases from 75 to 850° F. (25 to 455° C.).
2. As temperature increases from −100 to +75° F. (−75 to +25° C.) the alloy steels and non-ferrous metals show no regular change in their moduli. The carbon steels, however, show a regular decrease in modulus through this temperature range.
3. The modulus of KA-2 (stainless) steel is lower at all temperatures than that of any of the other steels.
4. Monel metal shows great superiority at all temperatures, to phosphor bronze and brass.
5. The presence of cold work causes an apparent increase in the modulus, this effect reaching a maximum around 180° F. (80° C.). An explanation for this effect is presented and embodies the idea that the "trapped" stresses in the cold-worked metal neutralize part of the applied stresses, thus causing the modulus to appear higher than it really is. A supplementary test was made in support of this explanation.

In a previous paper,[4] one of the authors defined the torsional modulus, discussed briefly its importance in engineering calculations and presented values of the torsional moduli of some common metals, as found in the literature and as determined by a series of personally conducted experiments. All the values reported were determined at atmospheric temperatures.

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[1] Chief Engineer, Barnes-Gibson-Raymond, Inc., Detroit, Mich.

[2] Associate Professor of Metallurgical Engineering, University of Michigan, and Consulting Metallurgist, Barnes-Gibson-Raymond, Inc., Ann Arbor, Mich.

[3] Assistant Investigator, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[4] W. P. Wood, "The Torsional Modulus of Carbon Steel, Phosphor Bronze, Brass, and Monel Metal," *Transactions*, Am. Soc. Steel Treating, Vol. XV, No. 6, p. 971 (1929).

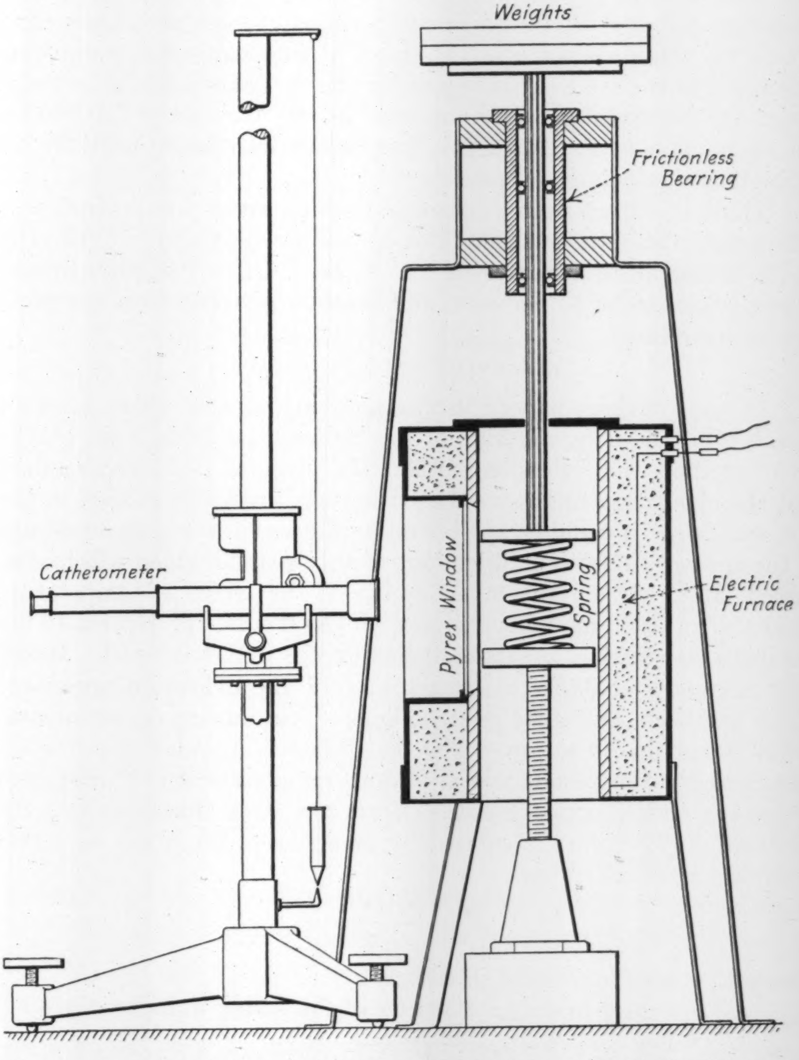

FIG. 1.—Apparatus for Determining Torsional Modulus by Deflection Method.

In many types of service at the present time it is necessary for springs and other torsion members to operate at temperatures other than atmospheric and it is the purpose of the present paper to present some further work, in connection with which the torsional modulus has been studied at temperatures above and below atmospheric.

There appear to be few published data on the variations in the torsional modulus of metals with temperature. Jasper[1] in an article on spring design gives the torsional modulus of steel at various temperatures. He does not give the chemical compositions nor previous treatment of the steel. His values for the torsional modulus average about 12,000,000 lb. per sq. in. at 100° F. (40° C.) and 10,750,000 lb. per sq. in. at 600° F. (315° C.). The results were based partially on theoretically calculated values.

Trade literature from a prominent spring manufacturer indicates a decrease in the torsional modulus of steel amounting to 20 per cent as the temperature increases to 800° F. (425° C.). Phosphor bronze shows a decrease of 50 per cent, and brass 35 per cent, over the same temperature range.

APPARATUS AND METHODS

In the previous paper,[2] it was pointed out that there are four methods for the determination of the torsional modulus, namely, the direct method, the deflection method, the torsional pendulum method and the elongation method. The deflection method was used in the first work since it could be applied under the actual working conditions of the spring. There are objections to this method which will be discussed later. When the investigation of the effect of temperature upon the torsional modulus was undertaken it was still decided to use the deflection method since the technique was well developed. It was only necessary to build a furnace around the deflection apparatus which had been previously used. Figure 1 is a drawing of the apparatus as it was finally set up. The sketch is self-explanatory. Deflections under various loads and at various temperatures were measured by means of the cathetometer. From the data thus obtained the torsional modulus was calculated by inversion of the usual deflection formula for helical springs:

$$F = \frac{8PD^3N}{Gd^4}$$

where F = total deflection in inches,
D = center to center diameter of the spring in inches,
P = load in pounds,
G = torsional modulus in pounds per square inch,
d = diameter of wire in inches, and
N = number of active coils

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[1] "The Value of the Energy Relation in the Testing of Ferrous Metals at Varying Ranges of Stress and at Intermediate and High Temperatures," *Philosophical Magazine*, Vol. 46, p. 609 (1923).

[2] *Loc. cit.*

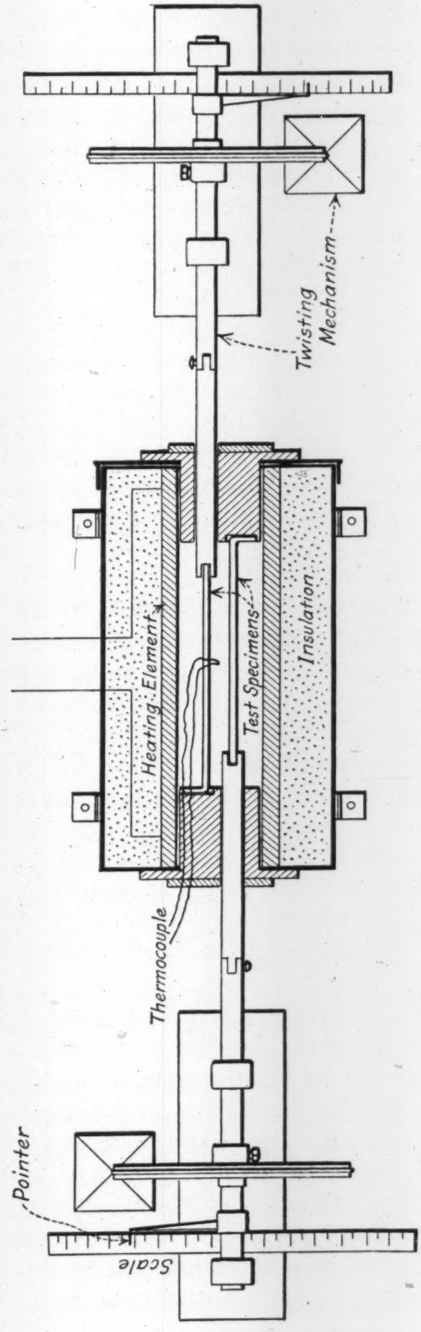
Twisting Mechanism
Test Specimens
Heating Element
Insulation
Thermocouple
Pointer
Scale

FIG. 2.—Apparatus for Determining Torsional Modulus by Direct Method.

There are two objections to the deflection method. In the first place the factor 8 is only constant over a certain range of ratios of wire diameter to spring diameter. It is of course possible to prepare springs which will possess the proper ratio but this rather limits the scope of the work. The second objection involves the fact that in a helical spring there are bending stresses present which, while small, would influence the value of the torsional modulus. In view of these two objections, the decision was made to study the torsional modulus by applying twisting moments to straight wire sections at various temperatures.

Figure 2 is a drawing of the apparatus used in determining the torsional modulus by the direct method. It consists of a horizontal electric furnace equipped at each end with a twisting device. A cast-iron plug fits into each end of the furnace through which the shaft of the twisting mechanism extends. Two specimens may be tested at one time with this apparatus. On one end the test specimen is held in a fixed position by a slot in the plug, while the other end is clamped into a slot in the twisting shaft by means of a set screw. All moving parts are mounted on ball bearings to reduce frictional losses to a minimum. The twisting moment is produced by weights supported by a wire which is attached to the periphery of a wheel. The angle of twist is measured to tenths of a degree by a movable pointer and fixed scale. The temperature is measured by a thermocouple whose hot junction is located at the center of the furnace. The shaft of the twisting mechanism consists of one piece upon which is mounted the pulley and pointer and another short piece to which the test specimen is clamped. These two pieces are fastened together by means of a slotted joint and set screw. The test specimens are approximately 10 in. in length and are held in the slots by right angle bends at each end of the wire.

Procedure:

The procedure in determining the torsional modulus was as follows: The test specimen was clamped to the short shaft and introduced into the furnace where by proper manipulation the other end of the specimen was inserted in the slot in the cast-iron plug at the opposite end of the furnace. The short shaft was then attached to the longer shaft and the furnace allowed to come to thermal equilibrium. In each case fifteen minutes was allowed for equilibrium to be reached after the furnace was at the desired temperature. With a few exceptions the entire series of metals was tested at one temperature before raising the temperature of the furnace. When thermal equilibrium was reached, an initial load of from ¼ to 1¼ lb. was applied (the amount depending upon the size of the wire being tested) and the pointer was set at zero on the scale. It was then possible to read directly the angle of twist produced by known loads and to calculate the torsional modulus. Two test specimens of each material were used. This gave six determinations for each material at each temperature, since three determinations were made on each test specimen by applying three different loads. In the majority of cases determinations of the torsional modulus were made in the temperature range of −100 to 600° F. (−75 to 315° C.), at intervals of 90° F. (50° C.). In the case of materials which showed up exceptionally well in this temperature range, the range extended to 850° F. (455° C.).

TABLE I.—CHEMICAL ANALYSES AND PREVIOUS TREATMENT OF SAMPLES.

Material	Wire Diameter, in.	Chemical Analysis						Treatment
		Carbon, per cent	Manganese, per cent	Phosphorus, per cent	Sulfur, per cent	Chromium, per cent	Other Elements, per cent	
Hard-drawn Steel...	0.135	0.65	1.03	0.030	0.035	....	....	Annealed and cold drawn
Carbon Steel (basic open-hearth)......	0.148	0.71	0.24	0.016	0.024	....	....	Quenched and drawn
Carbon Steel (crucible)............	0.136	0.90	0.34	0.030	0.027	....	....	Quenched and drawn
Music wire.........	0.138	0.92	0.31	0.020	0.020	....	....	Severely cold worked
Chromium-Vanadium Steel...	0.148	0.47	0.56	0.028	0.024	1.06	Vanadium 0.17	Quenched and drawn
Silico-Manganese Steel............	0.148	0.51	0.88	0.020	0.022	....	Silicon 1.45	Quenched and drawn
Nitralloy Steel (un-nitrided).........	0.152	0.39	0.56	0.021	0.016	1.95	Silcon 0.15 Aluminum 1.23 Molybdenum 0.18	As received
KA-2 Stainless Steel.	0.148	0.08	0.38	0.020	0.018	17.90	Silicon 0.58 Nickel 8.20	Annealed and cold drawn
High-speed Steel....	0.1875	0.70	0.30	under 0.025	under 0.025	4.00	Silicon under 0.20 Tungsten 18.00 Vanadium 1.00	Quenched from 2270° F. (1245° C.) Drawn at 1040° F. (560° C.)
Phosphor Bronze....	0.091	....	....	.....	.....	....	Copper 95.98 Tin 3.67	Annealed and cold drawn
Brass..............	0.135	....	....	.....	.....	....	Copper 66.04 Zinc 33.52	Annealed and cold drawn
Monel Metal.......	0.125	....	2.19	.....	.....	....	Copper 27.23 Nickel 69.6	Annealed and cold drawn

In the determination of the torsional moduli of the various metals at low temperatures the same apparatus was used. In this case only one end of the twisting device was used. One of the cast-iron plugs was taken out of the furnace and the tube packed with solid carbon dioxide, the test specimen having been previously inserted. The plug was then replaced in the end of the furnace, and the test specimen fitted into the slot. Additional carbon dioxide could be placed in the interior of the furnace through the hole in the plug through which the twisting shaft usually extended. This was done while waiting for equilibrium to be reached inside the furnace.

The determinations of the torsional modulus at room temperature were also made in this apparatus, the furnace being shut off. In all cases temperatures were read by the thermocouple and potentiometer indicator.

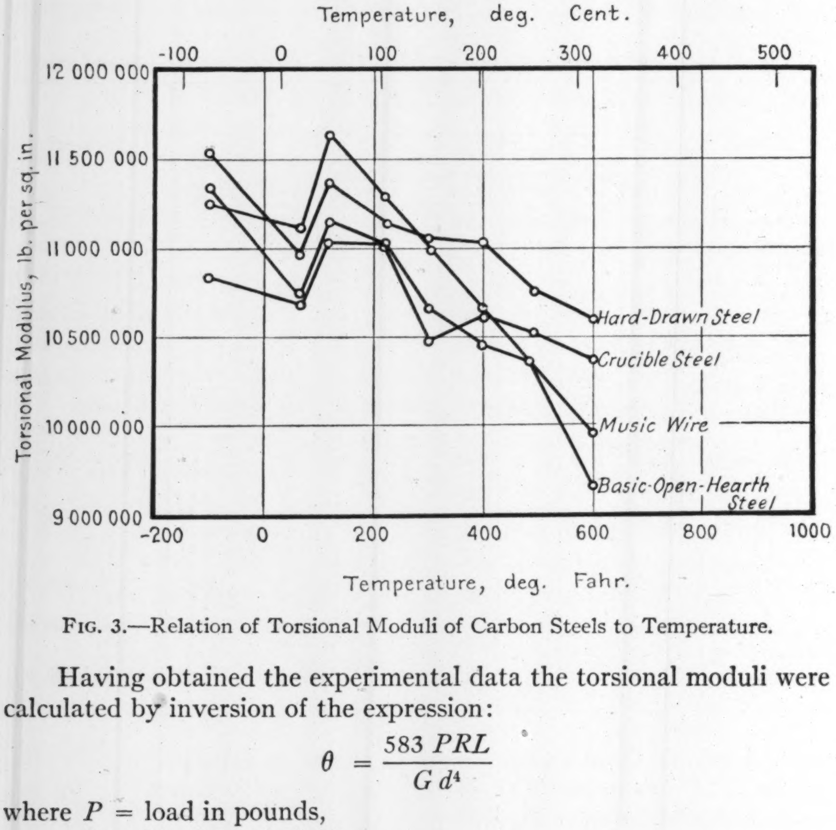

FIG. 3.—Relation of Torsional Moduli of Carbon Steels to Temperature.

Having obtained the experimental data the torsional moduli were calculated by inversion of the expression:

$$\theta = \frac{583\,PRL}{G\,d^4}$$

where P = load in pounds,
R = lever arm in inches,
L = length of test section in inches,
d = diameter of wire in inches,
θ = angle of twist in degrees, and
G = torsional modulus in pounds per square inch.

The average error in thermocouple readings was about ±5° F. (±3° C.). The overall error in the determinations of the torsional modulus were calculated to be about ±2 per cent.

MATERIALS INVESTIGATED

Table I gives the list of metals whose torsional moduli were determined, together with their chemical analyses and previous thermal and mechanical treatment. It was considered desirable to investigate all materials which were known to have been used in the production of helical springs as well as some which might possibly find future application in this field.

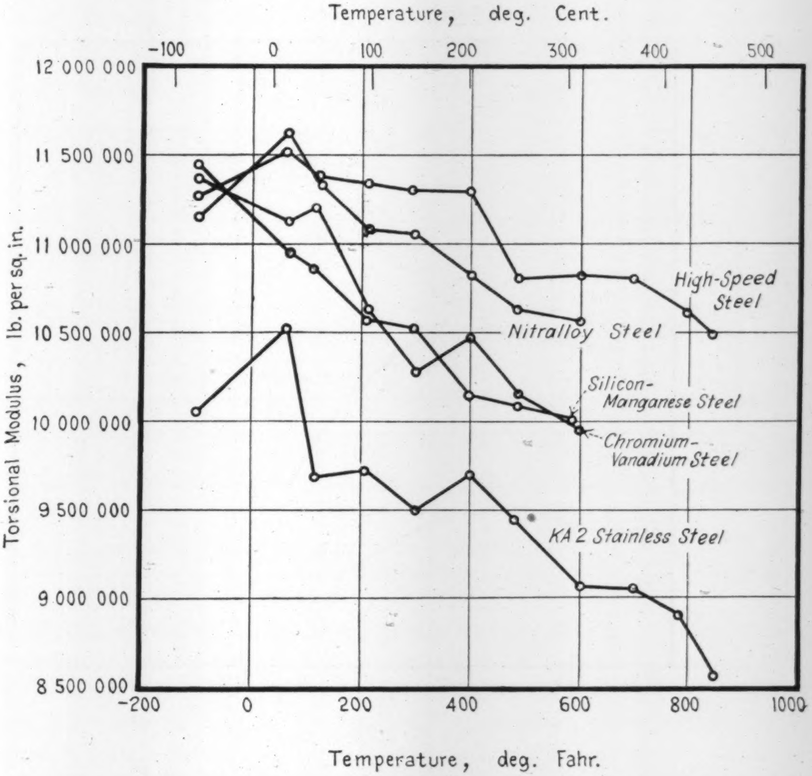

FIG. 4.—Relation of Torsional Moduli of Alloy Steels to Temperature.

RESULTS AND DISCUSSION

The results of this study are shown in the form of curves in Figs. 3, 4, and 5. As would be expected, there is a general downward trend in the moduli as temperature increases above atmospheric. The rate of decrease is not widely different in the alloy steels and carbon steels with the exception of heat-treated high-speed steel, which shows less general decrease up to 600° F. (315° C.) than any other steel. The hard-drawn steel holds up remarkably well until a temperature of 400° F. (205° C.) is reached.

No general conclusion seems evident as to the effect upon the alloy steels of temperatures below 0° F. (−20° C.). Some samples showed a tendency for the modulus to decrease as the temperature rose from −100° F. (−75° C.) to atmospheric temperature, while others showed the reverse effect. In general, the same point was observed in the case of the non-ferrous metals. The carbon steels, however, all showed higher values at sub-zero temperatures than at atmospheric.

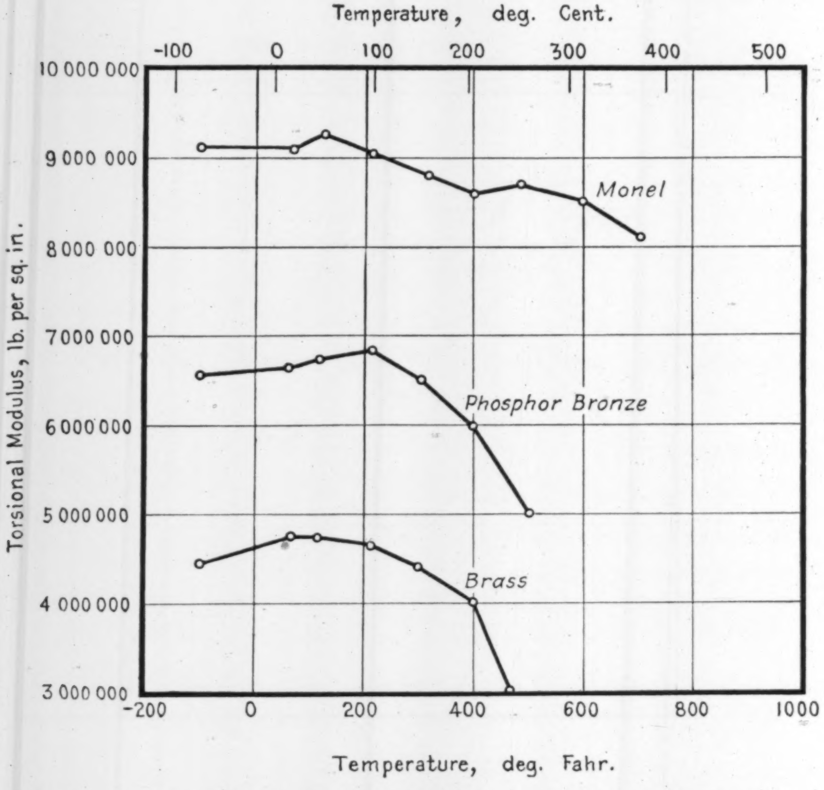

FIG. 5.—Relation of Torsional Moduli of Non-Ferrous Metals to Temperature.

It is interesting to note that the stainless steel known as KA-2 yielded values which are consistently lower than the other steels. It occupies a position about midway between monel metal and the steels containing greater amounts of carbon.

Of the non-ferrous metals, monel metal shows a distinct superiority to phosphor bronze and brass. So far as rate of decrease in modulus is concerned, monel metal compares very favorably with the steels. The decrease in the moduli of phosphor bronze and brass becomes very rapid above 200° F. (95° C.), while monel metal shows no similar tendency until a temperature of 600° F. (315° C.) has been reached.

Probably the most striking phenomenon which was observed was the marked increase in torsional modulus through the range 100 to 200° F. (40 to 95° C.). It will be noticed that, with one exception, the curves all show a maximum point in this range. Considerable effort was made to arrive at an explanation for this and it was finally decided that "trapped" stresses due to some cold work in the metal offer the most plausible explanation. Several investigators have reported improvement in yield point and general stress-strain relations as a result of heating slightly cold-worked steels at temperatures in the neighborhood of the boiling point of water. Among these might be mentioned Rees[1] and Van den Broek.[2]

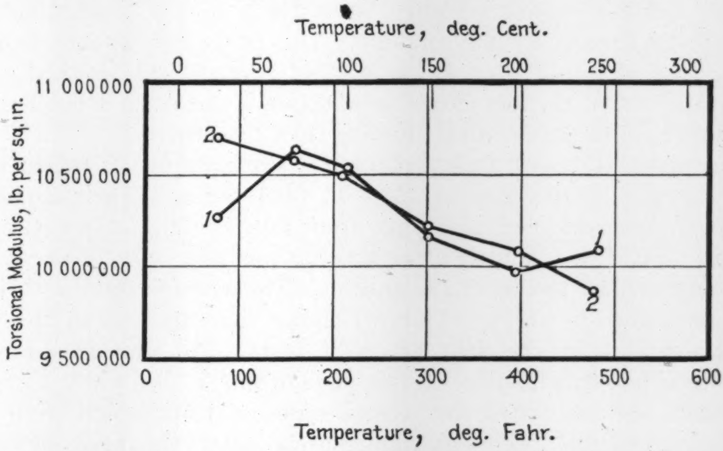

FIG. 6.—Torsional Moduli of Music Wire Annealed at 1625° F. (885° C.) and Cooled in Furnace.

As mentioned before, round wire sections were used in this study. Wire is received in coils and does not straighten out when the coil is released. In the case of all sections used, it was necessary to perform a straightening operation before the sections were subjected to test. In one case only—the silicon-manganese steel—were the sections straight when received. This steel, it will be noted, does not show the maximum point observed in all the others.

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[1] "Effect of Low-Temperature Annealing on Some Mechanical Properties of Cold-Drawn Steels," *Journal*, Iron and Steel Inst., Vol. CVIII, No. II, p. 273 (1923).

[2] "The Effects of Cold-Working on the Elastic Properties of Steel," The Iron and Steel Inst., *Carnegie Scholarship Memoirs*, Vol. IX (1918).

The effect of the stresses due to the cold work in the metals appears to reach a maximum around 200° F. (95° C.). Beyond this temperature the stresses are relieved and the modulus returns to a more normal value. Below 200° F. (95° C.) the "trapped" stresses are neutralizing part of the applied stress so that the resultant stress is less than the calculated applied stress. The strain is therefore smaller and the modulus higher, since the strain is divided into a larger stress than is actually present. This effect reaches a maximum in the case of music wire which is more severely cold-worked than any of the rest of the metals and in addition is put up in smaller coils, therefore requiring more straightening than the others.

In order to check this explanation two sections of music wire were thoroughly annealed at 1625° F. (885° C.) and their torsional moduli determined over the range from atmospheric temperature to 480° F. (250° C.). A little straightening was necessary in preparing these samples for test after the anneal. The average results of these tests are shown in Fig. 6. Curve 1 shows the variation in the torsional modulus in the first series of tests. An elevation in the modulus is noted as the temperature rises to 160° F. (70° C.). Curve 2 represents the results of the second series of tests which were run on the same test specimens immediately after the first series of tests and after all stresses were apparently removed. As will be noted, the curve shows a regular decrease in modulus with no maximum points.

Another point which is evident from a comparison of the curves in Fig. 6 with the curve for music wire in Fig. 3 is that the modulus in the annealed wire is lower all along the line than the modulus in the severely cold-worked wire, regardless of temperature.

It appears that the amount of cold work in a metal has a marked effect upon the values obtained for the torsional modulus and that many such values as previously determined are undoubtedly too high.

DISCUSSION

Mr. T. McL. Jasper[1] (*by letter*).—The values of the torsional modulus of steels at elevated temperatures is a very difficult matter to obtain accurately. For ordinary temperatures this is much more simple. It is believed that the values presented in this paper are not very accurately determined and do not represent usable values. This is indicated by the discontinuities shown by the curves presented in Figs. 3 and 4 of the paper.

The writer would very respectfully refer the authors to the work by W. Sutherland, published in the *Philosophical Magazine*, 1891, on "The Kinetic Theory of Solids," and also to another paper on "The Value of the Energy Relations in the Testing of Ferrous Metals at Varying Ranges of Stress and at Intermediate and High Temperatures," published in the *Philosophical Magazine*, October, 1923. The test results shown given in these publications give very consistent values for the torsional modulus as the temperature increases. The values of this modulus can be very accurately determined for metals by substitution in the following formula if the value at ordinary temperature is known:

$$\frac{F}{F_o} = 1 - \frac{T}{T_m}$$

where F = modulus of shear at any temperature absolute,
F_o = modulus of shear at zero temperature absolute,
T = the absolute temperature at which F is obtained, and
T_m = the absolute temperature at which the metal melts

It should be stated here that the general requirement for the application of this formula is an accurate determination of the modulus of shear at ordinary temperatures and a knowledge of the melting point of the metal in question.

The accompanying Fig. 1 shows the consistency of this relation when applied by actual modulus of shear measurements to several metals and Fig. 2 shows the experimental values obtained for carbon steels. Incidentally it might be suggested that the methods used by Sutherland are very sensitive and are designed to give very accurate results at elevated temperatures. This I believe was accomplished when the consistency of this relation as shown by his test results is

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[1] Director of Research, A. O. Smith Corp., Milwaukee, Wis.

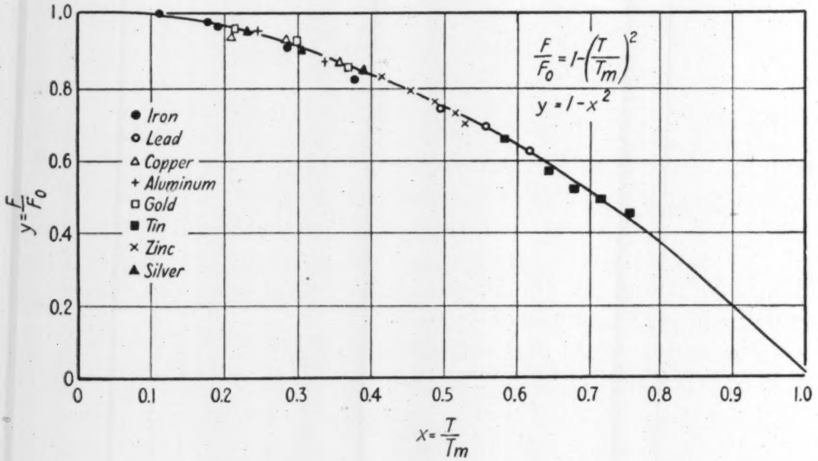

FIG. 1.—Showing the Variation of the Modulus of Rigidity or Shear at Various Temperatures Considering Several Different Metals.

The values as shown are taken from the results published from the work of nine investigators.

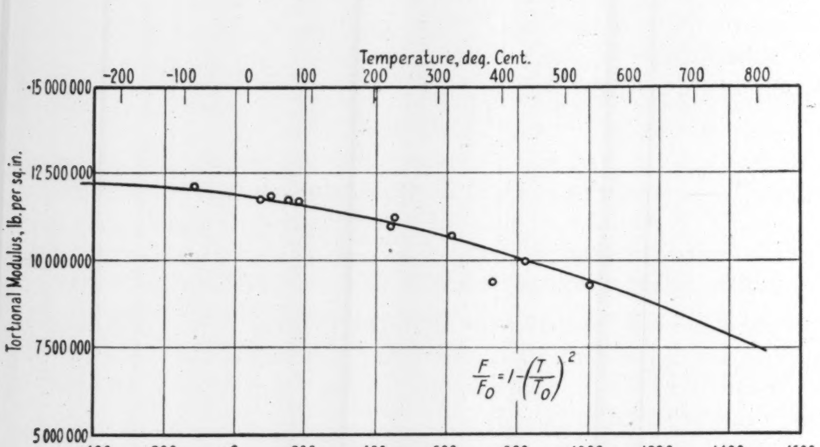

FIG. 2.—Showing the Variation for Steel of the Modulus of Shear or Rigidity with Temperature.

The plotted values are obtained experimentally and show average results of several investigators. The results in the neighborhood of atmospheric temperatures are the average of several determinations.

understood. The direct methods used in certain test results in the accompanying Fig. 2 show good consistency also and check with Sutherland's method.

The writer would very seriously criticize the test methods of the authors under the following heads:

1. Difficulty in determining the effective gage length of the specimen because of the point of load application and the recording device.
2. Difficulty in maintaining a temperature consistency over the entire effective gage length.
3. The assumptions necessary to be made in order to correct for the twist of the grip mechanisms, part of which was in the furnace, and part of which was outside of the furnace.

In discussing the elastic constants of steel these do not vary like the physical qualities as represented by the elastic limits, yield points or ultimate strengths. At ordinary temperatures the modulus of elasticity of various common steels vary at a maximum from about 29,000,000 to 31,000,000 lb. per sq. in. The modulus of rigidity or shear also varies in a manner appropriate to this ratio for definite temperatures. Small amounts of alloys in steel have very little effect on the elastic properties. At elevated temperatures up to 800° F. there is no reason to expect the variation shown by the curves presented by the authors. The test results shown in the accompanying Fig. 2 are measured values in which considerable care was taken to establish the effective gage length and also to establish a consistent temperature during the test over the whole effective gage length. The measuring mechanism was attached to the specimens at the points of effective gage length, thus eliminating the effect of twist on the grip and loading devices.

I cannot conceive the variation shown by the author's Fig. 4 to be possible with such little variation in the chemical composition.

The writer would very respectfully refer the authors to a paper entitled "Determination of Poisson's Ratio and a Suggestion for Its Use in Stress Analysis," presented before this Society in 1924.[1] In Table II of that paper is shown the great consistency between the modulus of rigidity of various steels with their compositions. The effect of composition on the elastic constants at ordinary temperatures is clearly shown, but its effect is of a very minor degree.

The writer would very seriously criticize the discussion on the effect of stresses due to cold work, etc., on the modulus of rigidity or shear. Such stresses affect the measured elastic limit but not the elastic properties except in a minor degree below the elastic limit of the steel which is understood to be the range in which work on modulus values applies. The specimen under so-called locked-up stress is in equilibrium when not under external load. The tensions are balanced by compressions and the effect can only be of a very minor order within the elastic limit of the steel.

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[1] T. McLean Jasper, "Determination of Poisson's Ratio and a Suggestion for Its Use in Stress Analysis," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 1012 (1924).

MESSRS. F. P. ZIMMERLI,[1] W. P. WOOD[2] AND G. D. WILSON[3] (*authors' closure by letter*).—The authors are grateful to Mr. Jasper for the discussion which he has submitted, particularly since it raises some controversial points which should if possible be settled.

The accuracy of the determinations is questioned on the basis of irregularities in the curves. The authors are aware that many curves are drawn on the basis of the general direction indicated by a sequence of data but feel that this is a dangerous practice since in so many cases local variations may be entirely missed or misinterpreted. Smooth curves could have been drawn in the general directions indicated by the data obtained in this investigation but the authors feel that this would have been dodging the explanation of some persistent variations which were observed when the curves were plotted exactly as obtained. As stated in the paper, each point on the curves was established as the average of six determinations.

Mr. Jasper makes reference to some work by Sutherland[4] on the determination of the torsional modulus. Reference to this paper reveals the fact that Sutherland carried out his determinations of the torsional modulus at various temperatures in a vertical wooden box, the temperature being regulated by means of a gas flame in one of the lower corners of the box. The temperature was read by means of a thermometer suspended in the box near the central portion of the wire. No determinations were made above 110° C.

The authors cannot help but feel that the apparatus used by them and described in the paper affords a much wider range of temperature as well as better control. A recent exploration of the temperatures within their furnace has showed a maximum variation of ± 10° C. at 350° C. with smaller variations at lower temperatures. While Sutherland makes no statement as to the temperature variations within his wooden box it seems very doubtful that his control of temperature was even as good as that of the present investigation.

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[3] Assistant Investigator, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[4] William Sutherland, "Kinetic Theory of Solids," *Philosophical Magazine*, Vol. XXXII, p. 31 (1891).

Mr. Jasper points out a possible error in the measurement of the effective gage length of the specimens. The authors had this error in mind when they chose a 10-in. gage length. Calculations show that a variation of 0.1 in. in the measurement of the gage length introduces an error of only 1 per cent, and all measurements of specimens by the authors were made to 0.01 in. by means of a vernier caliper. This error is well within the 2-per-cent over-all variation observed by the authors.

Another point questioned by Mr. Jasper involves a possible error introduced by the fact that the twisting mechanism was outside the furnace and that part of the measured twist would be in this portion of the mechanism. The authors also had this point in mind while designing the apparatus and made the twisting shaft of $\frac{3}{4}$-in. section to minimize this error. With the maximum twisting moment used in the investigation this error amounts to 0.0000027 deg. In this latter calculation a torsional modulus of 10,000,000 was used to allow for the fact that some of the parts were quite hot.

Mr. Jasper contends that the torsional moduli of the various metals decreases with increase of temperature at a regular rate as shown by the relation $F/F_o = 1 - T/T$. This is based upon the assumption that metals and alloys are homogeneous and isotropic from 0° absolute to their melting points. Many alloys consist of more than one constituent and can hardly be considered as homogeneous. Even if only one constituent be present, it may show variations in composition and properties which again make this assumption difficult. Metals and alloys whose structures consist of unstrained crystals of uniform size probably approach the state of being isotropic, but if their structure has been modified by mechanical or thermal means, the assumption of isotropy is certainly open to question. Further, the presence of transition points will cause changes in the properties of metals and alloys which will change the physical constants.

One of the terms appearing in the above relation is the melting point of the metal. In the case of alloys, the melting point frequently does not occur at a single temperature but over a range of temperature. Under these conditions what value is going to be substituted in the formula? Recent work on the properties of metals and alloys at elevated temperatures has shown that above a certain minimum temperature which is believed to be the lowest temperature of recrystallization, metals show a decided change in their elastic properties. Above this temperature metals behave more like plastic bodies than elastic bodies. The amount of deformation under any load depends entirely upon the time factor. It would therefore be possible to obtain most any value for the physical constants that one desired. In the light of this information the authors contend that the universal application of Mr. Jasper's relation is impossible.

Figure 2 of Mr. Jasper's discussion presents a curve showing plotted values of the variation of the torsional modulus of steel *versus* temperature. In the accompanying Fig. 3 the authors present a similar curve which was obtained by plotting the points in Mr. Jasper's figure on the same scale as used in the paper. It will be seen that this replotted curve shows about as many variations as the authors' original curves including an increase of the modulus in the neighborhood of 100° F. In this connection the authors desire to draw attention to a similar curve for mild steel presented by Lea.[1] It also shows a halt and increase between 100 and 200° C. It is this break in the curve which the authors have noted repeatedly and for which they have sought an explanation. In some earlier work carried out by the authors they had occasion to observe deflections in helical compression springs under constant load but increasing temperature.

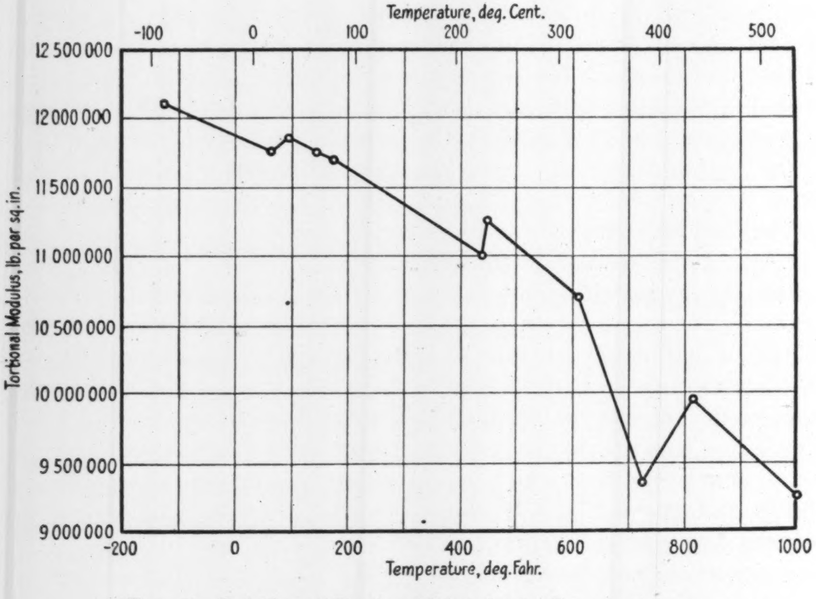

FIG. 3.—Relation of Torsional Modulus to Temperature.

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[1] F. C. Lea, "The Effect of Temperature on Some of the Properties of Metals," *Engineering*, Vol. 113, p. 829 (1922).

In practically all cases deflections decreased up to about 150° F., and beyond that point showed a steady increase. A temperature-deflection curve is shown for one of these springs in the accompanying Fig. 4. It would appear that the only factor which could cause this phenomenon is a variation in the torsional modulus.

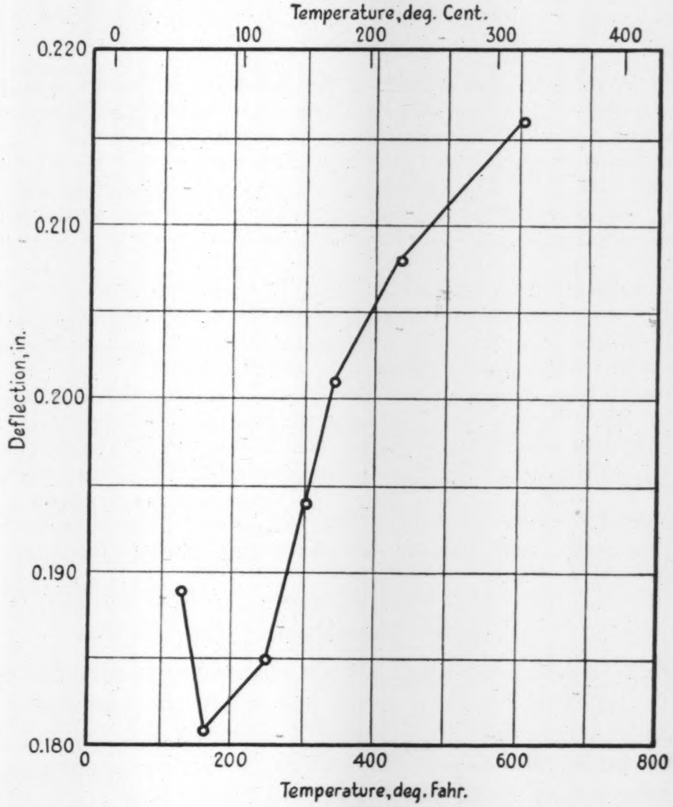

FIG. 4.—Relation of Deflection of Steel Helical Spring at Constant Load to Temperature.

In conclusion, the authors beg to differ with Mr. Jasper in the values of the torsional moduli of some common metals at atmospheric temperatures as reported in his paper. He reports values above 12,000,000 lb. per sq. in. for all carbon steels. The authors' work as well as the work of other investigators has shown this value to be about 11,500,000 lb. per sq. in. His value for monel metal is also about 1,000,000 lb. per sq. in. higher than the value given in International Critical Tables and as determined by the authors.

THE EFFECT OF UNDER-STRESSING ON CAST IRON AND OPEN-HEARTH IRON

By J. B. Kommers[1]

Synopsis

Many investigators have reported that repeated stresses at or just below the endurance limit will strengthen material, so that the new endurance limit is higher than before. Some materials are known to be much more susceptible to such action than others. With the idea of studying some of these influencing factors, and with the hope of increasing our knowledge of fatigue phenomena, the author has made under-stressing tests on gray cast iron, a relatively non-homogeneous material, and on Armco open-hearth iron, a very homogeneous material.

Two of the influencing factors which have been studied involve the determination of the optimum unit stress and the optimum number of cycles for producing the maximum strengthening effect. The difference in the behavior of cast iron and Armco iron is pointed out and discussed.

The more homogeneous Armco iron seems to be susceptible of a less percentage of strengthening than the non-homogeneous cast iron—about 10 per cent compared to a maximum of 31 per cent for cast iron. This seems to be because in an ordinary fatigue test the Armco iron develops a greater proportion of the maximum possible endurance limit than does the cast iron.

The paper also presents the results of fatigue and under-stressing tests on notched specimens, and explains the contrasting phenomena observed for Armco iron and cast iron.

Introduction

Fatigue experiments have shown that when a material is subjected to repeated stresses at or just below the endurance limit, called under-stressing, the material is strengthened so that it can withstand higher repeated stresses than the original endurance limit. This strengthening effect has been observed with steels, cast irons, non-ferrous metals, and even with concrete. There seems, however, to be a great difference with different materials in the percentage of strengthening which can be obtained. The present paper is an attempt to make a beginning in the investigation of the factors which influence this strengthening effect.

Two factors that influence the strengthening obtained by under-stressing, and which will be discussed in this paper, are the number of cycles and the unit stress employed in under-stressing. It will be of interest to know whether there is an optimum number of cycles and an optimum unit stress which produce the greatest strengthening effect.

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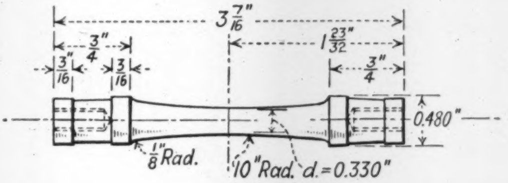
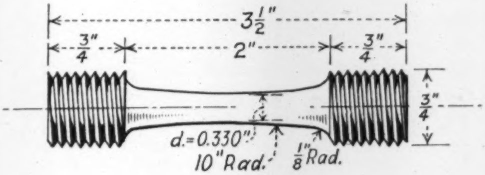
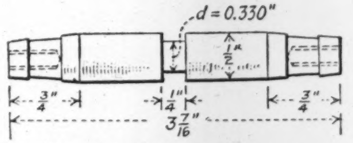
There is some evidence that the more homogeneous a material is, the less it is susceptible to strengthening due to repeated stresses. For instance, the greatest percentage of strengthening due to under-stressing reported hitherto, so far as the author is aware, is that reported for a gray cast iron by Moore, Lyon, and Inglis.[1] In one case they observed a strengthening of about 43 per cent. In a single specimen of 0.37-per-cent carbon steel in the sorbitic condition, Moore and Jasper[2] found a strengthening of 65 per cent, but three other specimens were strengthened only from 20 to 25 per cent.



Fatigue Specimen.



Tension Specimen.



Notched Fatigue Specimen.

FIG. 1.—Test Specimens.

Under-stressing in fatigue may be looked upon as repeated cold work, and it is of interest to note the effects of static cold work, such as cold drawing, on the endurance limit. The author has made some tests, as yet unpublished, on 80–20, 70–30, and 60–40 brasses.

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[1] *Bulletin No. 164*, Engineering Experiment Station, University of Illinois, 1927.

[2] *Bulletin No. 142*, Engineering Experiment Station, University of Illinois, 1924.

The 80–20 and the 70–30 brasses consist of one phase; the 60–40 brass consists of two phases, and is therefore less homogeneous than the other two. The brasses as received were in the cold-drawn condition, having had the length increased about 33 to 36 per cent in the last pass after annealing. Some of the 80–20 and the 70–30 brass was annealed at about 1100° F., and some 60 – 40 brass was annealed at about 1300° F. Comparing the cold-drawn with the annealed material, the following was observed:

Brasses	Increase in Strength Due to Cold Work Tensile Strength, per cent	 Endurance Limit, per cent
80–20	61	–4
70–30	57	0
60–40	30	24

The effect of the static cold work on the endurance limit was therefore most effective for the 60–40 brass and least effective for the 80–20 brass.

Table I.—Chemical Analyses of Materials.

Material	Total Carbon, per cent	Combined Carbon, per cent	Graphitic Carbon, per cent	Manganese, per cent	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent
Cast iron	3.46	0.43	3.03	0.61	2.19	0.129	0.27
Hot-rolled Armco iron	....	0.015	....	0.03	0.01	0.050	0.007
Cold-drawn Armco iron	....	0.04	....	0.02	0.03	0.032	0.005

Further comparisons of the cold-drawn material with material given a low temperature anneal for one hour at 525° F. again showed least increase in tensile strength and greatest increase in endurance limit for the 60–40 brass. These results should be looked upon as tentative indications.

Materials and Specimens Used for the Present Tests

The materials which were chosen for the present tests were a low-strength gray cast iron, and hot-rolled and also cold-drawn open-hearth iron manufactured by the American Rolling Mill Co. For convenience, this will be referred to by its customary name, Armco iron. Cast iron was chosen as representing a brittle, non-homogeneous material, and Armco iron as representing a ductile, homogeneous material.

The cast-iron bars were furnished in the form of A.S.T.M. arbitration bars, 15 in. long; the hot-rolled Armco iron bars were 1 in. in diameter; and the cold-drawn Armco iron bars were $\frac{1}{2}$ in. in diameter.

The cast-iron bars were all poured from one ladle at a temperature of approximately 2500° F. The metal charge going into the cupola was made up of 45 per cent of pig iron, 10 per cent of steel, and 45 per cent of cast scrap. The chemical analyses of the materials are given in Table I.

Tensile properties and hardness of these materials are given in Table II. The cast-iron tension test specimen had a minimum diameter of 0.33 in., and was made with a smoothly changing diameter by swinging the cutting tool on a 10-in. radius as shown in Fig. 1. The hot-rolled Armco-iron tension test specimen had a diameter of $\frac{1}{2}$ in., and the cold-drawn Armco-iron specimen a diameter of $\frac{1}{4}$ in.

Figure 1 shows the standard and notched fatigue specimens used in the tests. The diameter of the notched specimen is the same as the minimum diameter of the standard specimen. The standard fatigue specimens of both Armco iron and cast iron were turned on a lathe and then ground. They were polished with emery flour and oil using French papers Nos. 0 and 00. The polishing was finished on a buffing wheel using jewellers' rouge. The notched fatigue specimens were turned in a lathe, and polished with emery flour and oil, using French papers Nos. 0 and 00. Four R. R. Moore fatigue machines were used in making the fatigue tests.

TABLE II.—TENSILE PROPERTIES AND HARDNESS OF MATERIALS

Material	Tensile Strength, lb. per sq. in.	Proportional Elastic Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Rockwell Hardness	Brinell Hardness
Cast iron	20 000	.....	.....	....	....	B91	174
Hot-rolled Armco iron	44 300	21 300	22 700	47.0	75.1	B53	83
Cold-drawn Armco iron	73 100	.....	69 200	11.7	63.0	B87	142

EFFECT OF NUMBER OF CYCLES OF UNDER-STRESSING

To determine the effect which the number of cycles of preceding under-stress had on the increase of endurance limit, it was thought best to make the tests on cast iron, because this metal had shown the greatest susceptibility to strengthening, and therefore would be more likely to register small differences in number of applied cycles. The procedure in the fatigue tests was to subject a series of specimens to a given number of cycles of under-stress, say 5,000,000, and then to determine the endurance limit in the ordinary way. If a specimen in the final test withstood from 6,000,000 to 10,000,000 cycles without failure, it was assumed that the endurance limit had not been exceeded. This procedure was based on the fact that the *S-N* diagram for cast iron usually shows a break in the curve at 1,000,000 cycles or less. In determining the endurance limit, it should be understood that "coaxing," in which the unit stress is applied by increasing increments, was not employed. Each specimen in the final fatigue test was subjected to a constant unit stress, and either failed or did not fail under that stress.

The endurance limit of the cast iron as received had been determined at a value of 9300 lb. per sq. in., and in order to prevent the possibility of failures at this value of stress during the under-stressing part of the test, a value of about 9000 lb. per sq. in. was chosen as the stress to be used for under-stressing. The stresses applied in all these tests differed from 9000 lb. per sq. in. by amounts which were usually less than 80 lb. per sq. in. Table III gives a summary of the results. Figure 2 shows the percentage increase in endurance limit with increase in the number of cycles of under-stress. The maximum increase in endurance limit is about 25 per cent, which was obtained by under-stressing for 15,000,000 cycles or over. An increase in the number of cycles beyond 15,000,000 did not result in any further increase of endurance limit. One-half of the maximum increase in

TABLE III.—EFFECT OF NUMBER OF CYCLES USED IN UNDER-STRESSING CAST IRON.

Original Endurance Limit: 9300 lb. per sq. in.
Unit Stress Used in Under-stressing: 9000 lb. per sq. in.

CYCLES OF APPLIED UNDER-STRESS	NEW ENDURANCE LIMIT, LB. PER SQ. IN.	INCREASE OVER ORIGINAL ENDURANCE LIMIT, PER CENT
2 500 000	10 500	12.9
5 000 000	11 000	18.3
10 000 000	11 200	20.4
15 000 000	11 600	24.7
20 000 000	11 600	24.7
30 000 000	11 600	24.7
40 000 000	11 600	24.7

TABLE IV.—EFFECT OF UNIT STRESS USED IN UNDER-STRESSING CAST IRON.

Original Endurance Limit: 9300 lb. per sq. in.
Number of Cycles of Under-stress Applied: 20,000,000

UNIT STRESS USED IN UNDER-STRESSING, LB. PER SQ. IN.	NEW ENDURANCE LIMIT, LB. PER SQ. IN.	INCREASE OVER ORIGINAL ENDURANCE LIMIT, PER CENT
9300	12 200	31.2
9000	11 600	24.7
8500	11 400	22.6
8000	10 800	16.1
7500	10 800	16.1
7000	10 800	16.1
6500	10 800	16.1

endurance limit was obtained during the first 2,500,000 cycles of applied under-stress. Later tests (Table IV) show that if the unit stress used in under-stressing had been 9300 instead of 9000 lb. per sq. in., the maximum endurance limit would have been 12,200 instead of 11,600 lb. per sq. in.—an increase due to under-stressing of 31 per cent.

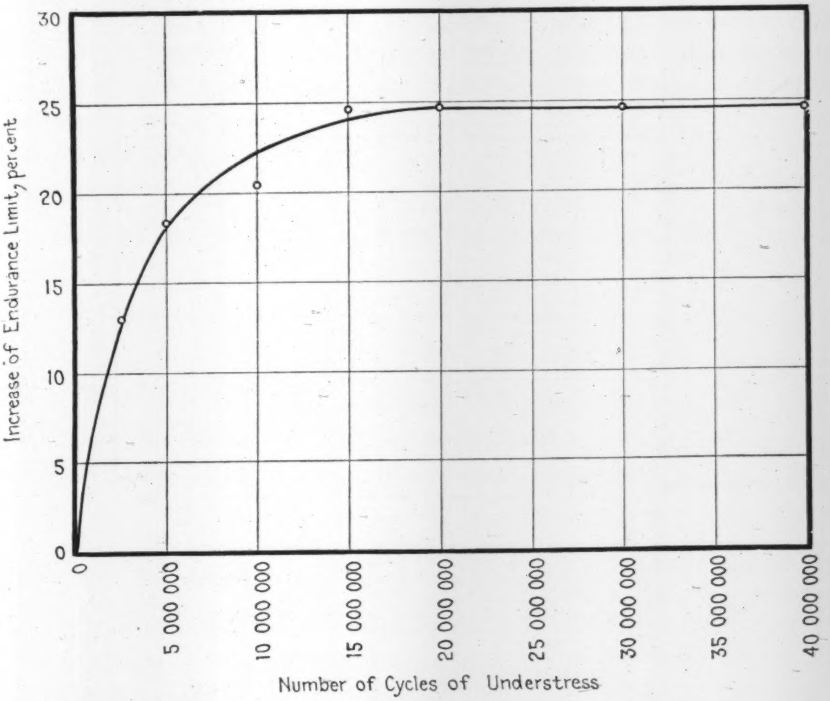

FIG. 2.—Effect of Number of Cycles Used in Under-stressing Cast Iron.

EFFECT OF UNIT STRESS USED IN UNDER-STRESSING

To determine the value of the unit stress which would be most effective in increasing the endurance limit due to under-stressing, a second series of tests was carried out, in which specimens were subjected to 20,000,000 cycles at certain unit stresses and then the new endurance limits determined. Twenty million cycles were selected as having been shown in the previous tests to be sufficient to produce maximum strengthening. Here again "coaxing" was not used. Table IV shows the results of these tests. Figure 3 shows the increase in endurance limit as the unit stress used in under-stressing was increased.

From Table IV it is evident that the most effective unit stress to produce strengthening due to under-stressing is one that is as close to the original endurance limit as possible. It is also evident that as the unit stress used in under-stressing is reduced, the strengthening effect is also reduced, until a unit stress of 8000 lb. per sq. in. is reached, after which the strengthening effect is constant, at least down to 6500 lb. per sq. in. In other words, a decrease of the applied unit stress used in under-stressing of about 16 per cent reduces the strengthening effect to about one-half of the maximum amount possible.

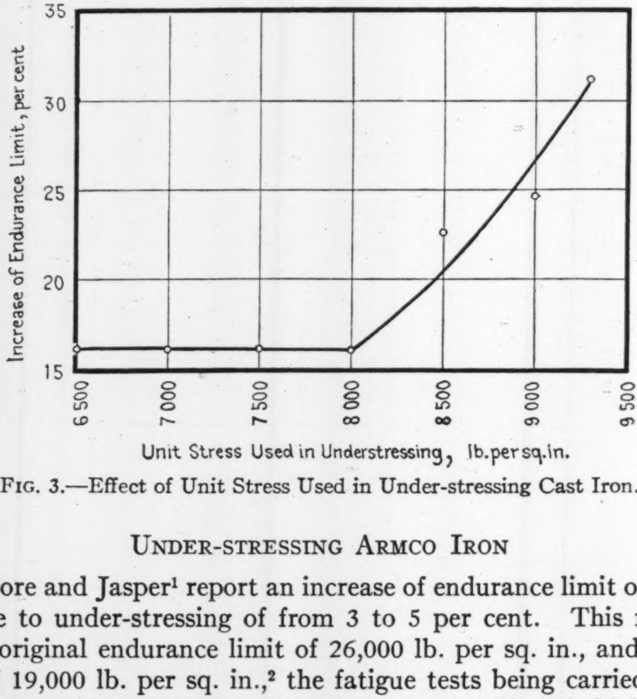

FIG. 3.—Effect of Unit Stress Used in Under-stressing Cast Iron.

UNDER-STRESSING ARMCO IRON

Moore and Jasper[1] report an increase of endurance limit of Armco iron due to under-stressing of from 3 to 5 per cent. This material had an original endurance limit of 26,000 lb. per sq. in., and a yield point of 19,000 lb. per sq. in.,[2] the fatigue tests being carried out to 100,000,000 cycles. The fact that the endurance limit is higher than the yield point is evidence that in a fatigue test of this material there is a strengthening and a destructive effect proceeding simultaneously. When the stress of 26,000 lb. per sq. in. is first applied, the most highly stressed fibers will yield by slipping in the crystals. If the slipping continued with increase in number of applied cycles of stress a crack would inevitably be developed. The fact that even 100,000,000 cycles did not cause failure at this stress indicates that the original slip ceased in time, and that the material was strengthened so that it was elastic at least up to 26,000 lb. per sq. in. Experiments on concrete have shown that for a stress within the endurance limit the first few cycles produce permanent deformation or inelastic behavior.[1] With increase in number of cycles the material adjusts itself to the stress imposed, the stress-deformation curve becomes a straight line, and the material now seems to be perfectly elastic.

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[1] *Bulletins Nos. 136 and 142*, Engineering Experiment Station, University of Illinois, 1922, 1923.

[2] *Bulletin No. 124*, Engineering Experiment Station, University of Illinois, 1921.

The yield point, tensile strength and endurance limit (standard specimen) of the hot-rolled and cold-drawn Armco iron are given for comparison in Table V. It is seen that the effect of the cold work has been to increase the yield point by 205 per cent and the tensile strength by 65 per cent—both quite substantial increases—and the endurance limit by 27 per cent. Apparently the strain hardening due to cold drawing must have had a strengthening and a destructive effect. The strengthening effect evidently made it more difficult for a crack to propagate, and at the same time probably so disturbed the crystals that many minute flaws were introduced, which made it easier for a crack to start. The ease with which a crack could start prevented the endurance limit from being raised up to the new yield point which the cold rolling had conferred upon the material.

TABLE V.—ENDURANCE LIMITS, WITH TENSILE PROPERTIES FOR COMPARISON.

Material	Endurance Limit, Standard Specimen, lb. per sq. in.	Endurance Limit, Standard Specimen, Under-stressed 20,000,000 Cycles, lb. per sq. in.	Endurance Limit, Notched Specimen, lb. per sq. in.	Endurance Limit, Notched Specimen, Under-stressed 20,000,000 Cycles, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Ratio, Endurance Limit to Tensile Strength	Ratio, Endurance Limit to Yield Point
Gray cast iron........	9 300	12 200	9 300	.....	20 000	.....	0.465	....
Hot-rolled Armco iron.	26 200	28 700	18 500	20 100	44 300	22 700	0.59	1.15
Cold-drawn Armco iron	33 300	.....	.....	.....	73 100	69 200	0.46	0.48

It should be observed in passing that the value of endurance limit for the cold-drawn Armco iron is undoubtedly decreased because of the presence of internal stresses due to the cold-drawing. This fact, however, does not vitiate the general argument presented above.

This argument is strengthened by the observed behavior of the hot-rolled and cold-drawn Armco iron. Applying a stress of 3500 lb. per sq. in. greater than the yield point in the fatigue test, making a total stress of 26,200 lb. per sq. in., evidently enabled the hot-rolled

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[1] H. F. Moore and J. B. Kommers, "The Fatigue of Metals," p. 276, McGraw-Hill Book Co., Inc., New York City.

Armco iron to become strain-hardened and perfectly elastic up to a unit stress of the applied amount without starting minute cracks. The tests on the cold-drawn Armco iron show that it may be strain-hardened against fatigue at least up to 33,300 lb. per sq. in. If a unit stress higher than 26,200 lb. per sq. in. is applied to hot-rolled Armco iron in a fatigue test, evidently the production of minute flaws more than overbalances the strengthening due to repeated cold work, with the result that the specimen finally fails.

Under-stressing tests on hot-rolled Armco iron were carried out by applying a unit stress at or just below the endurance limit. An arbitrary limit of 20,000,000 cycles was employed, although it was not determined that this number of cycles would produce the maximum effect on this material. The previous discussion would lead one to expect that such under-stressing would have very little effect in increasing the endurance limit. The material in the original fatigue test, when stressed to its endurance limit, was being strain hardened by a stress which was higher than the yield point. Therefore, stressing the specimen just below the endurance limit would simply subject the material to a strain hardening effect similar to that received in the regular fatigue test. This under-stressing might produce a slight increase in endurance limit if the applied stress were slightly below the original endurance limit, because with the slightly lower stress the strain hardening presumably would overbalance slightly the production of minute flaws. The tests actually showed that the endurance limit was increased by under-stressing from 26,200 to 28,700 lb. per sq. in., or only about 10 per cent.

TESTS ON NOTCHED HOT-ROLLED ARMCO IRON

The endurance limit of the notched hot-rolled Armco iron, using the notched specimen illustrated in Fig. 1, was found to be 18,500 lb. per sq. in. (Table V), a reduction of 29 per cent due to the notch. When this specimen is stressed to a nominal stress of 18,500 lb. per sq. in., a strengthening tendency and a destructive tendency are operating at the corner of the notch. The strengthening tendency due to the repeated cold work is evidently not rapid enough to prevent the development and spread of a crack. It is well known that at the corner of the square notch, the actual local stress is much higher than the nominal stress. This local stress is not, however, as great as the mathematical theory of elasticity would indicate for stresses within the elastic limit, for the reason that the material is not perfectly elastic and actually yields. When the material yields, it is cold-worked by the repeated stresses. The stress at the notch falls off very rapidly with distance from the corner, as is well known for such cases, and presumably at a nominal unit stress equal to the endurance limit the strengthening effect at the notch, or a few crystals away from the notch, is balanced by the destructive effect at the notch. If a lower stress than the nominal stress of 18,500 lb. per sq. in. is applied, failure will not occur, because the destructive effect at the notch is prevented from propagating a crack by the strengthened material at the notch or a few crystals away.

When a notched specimen is subjected to a nominal stress of 19,000 lb. per sq. in., the deformation at the notch is evidently so great that the material is not strengthened rapidly enough to prevent the propagation of a crack. The effect of the notch is evidently such as to produce a deformation corresponding to a unit stress of 7700 lb. per sq. in., the difference in endurance limits of the notched and unnotched specimen.

If, when a notched specimen is subjected to a nominal unit stress of 18,500 lb. per sq. in., the material at the corner of the notch is strengthened just as much as the material in a standard specimen, then it is evidently strengthened at least from the yield point up to 26,200 lb. per sq. in., an amount of 3,500 lb. per sq. in. In that case, the actual unit stress at the notch when a nominal stress of 18,500 lb. per sq. in. is applied would be 26,200 lb. per sq. in. Understressing just below 18,500 lb. per sq. in. would therefore not be expected to strengthen the material very much. This was confirmed by understressing the notched specimen with a nominal unit stress of 18,400 lb. per sq. in. for 20,000,000 cycles. This increased the endurance limit from 18,500 to 20,100 lb. per sq. in. (Table V), or about 9 per cent. Evidently the material at the notch was strengthened by understressing, so that when higher stresses were applied the deformation at the notch was not so great as for virgin material subjected to the same stress. In this way the endurance limit was increased 9 per cent, which is slightly less than the 10 per cent obtained on the standard specimen.

It should be noted that the standard specimen had its endurance limit increased by 2500 lb. per sq. in., while the notched specimen was strengthened only 1600 lb. per sq. in.

TESTS ON NOTCHED GRAY CAST IRON

If the carbon flakes, non-metallic inclusions, etc., in gray cast iron may be looked upon as producing notches, then the low endurance limit of cast iron may be explained by the fact that at these notches there exist high localized stresses. If iron can be cold-worked and have its endurance limit increased by cold work (and this is actually the case), it is possible to conceive of the strengthening due to under-stressing as being due to repeated cold work.

The situation for cast iron when stressed slightly above the endurance limit is somewhat different from that of Armco iron under the same conditions. When hot-rolled Armco iron is stressed somewhat above 26,200 lb. per sq. in., the stress is above the yield point, and failure occurs because the slipping in the crystals finally develops a crack. The very fact that the endurance limit is higher than the yield point indicates that there is no special factor in the nature of a flaw which causes failure. In cast iron, on the other hand, the high localized stresses at the notches due to carbon flakes, etc., start cracks which finally cause failure. If the metal at the bottom of these notches can be strengthened, it will be possible to obtain higher endurance limits for cast iron due to under-stressing.

Consider a steel, normalized, and with about 0.52 per cent of carbon. Moore and Kommers[1] found that such a steel had an endurance limit of 42,000 lb. per sq. in. A cast iron with 0.54 per cent of combined carbon tested by the author[2] showed an endruance limit of 12,000 lb. per sq. in. The effect of the carbon flakes, etc., apparently is such as to reduce the endurance limit about 30,000 lb. per sq. in., or 71 per cent. It is of interest to compare with this a 0.49-per-cent carbon steel in the sorbitic condition. The effect of a square notch (as shown by Moore and Kommers)[1] was to reduce the endurance limit from 48,000 to 23,000 lb. per sq. in., or 51 per cent.

If a specimen of cast iron, which already has carbon notches in it, is provided with a square notch, the percentage reduction in endurance limit would not be expected to be as much as 50 per cent.

The actual results obtained by experiment were rather surprising. The gray cast iron, using a standard specimen, gave an endurance limit of 9300 lb. per sq. in. Using a notched specimen, as shown in Fig. 1, the endurance limit was practically the same, and indeed quite a number of specimens withstood higher stresses for from 10,000,000 to 20,000,000 cycles. This result indicates that the concentration of stress at the corner of the square notch was no more serious than the carbon notches originally in the cast iron. Of fourteen notched specimens tested, seven broke at the corner of the notch and seven away from the corner of the notch.

The gray cast iron used in the present tests contained 0.43 per cent of combined carbon. It will be interesting to examine the results obtained on steel of approximately the same amount of carbon. Moore and Kommers[1] reported results on normalized 0.37 and 0.52-per-cent carbon steel. The endurance limits were 33,000 and 42,000 lb. per sq. in., respectively. Moore and Jasper[2] reported that these steels could be strengthened by under-stressing about 21 and 16 per cent, respectively. Let it be assumed, therefore, that a 0.43-per-cent carbon steel would have an endurance limit of 36,000 lb. per sq. in., and that it would be strengthened 19 per cent by under-stressing,or 6800 lb. per sq. in. The gray cast iron of the present tests had an endurance limit of 9300 lb. per sq. in. If the iron at the carbon-flake notches could be strengthened by 6800 lb. per sq. in., due to under-stressing, the new endurance limit would be 16,100 lb. per sq. in., an increase of 73 per cent. The maximum increase obtained in the present tests was 31 per cent, as has been previously pointed out.

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[1] *Bulletin No. 124*, Engineering Experiment Station, University of Illinois, 1921.

[2] J. B. Kommers, "The Static and Fatigue Properties of Some Cast Irons," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 174 (1928).

This discrepancy may, of course, be explained as follows: The steel with 0.43 per cent carbon could be strengthened 6800 lb. per sq. in. using a standard fatigue specimen. If the specimen had been notched, presumably the presence of the notch would have reduced the endurance limit and also the net amount of strengthening due to under-stressing. The notches in the cast iron due to the carbon flakes prevent the iron from being strengthened as much as 6800 lb. per sq. in. That this argument is sound is shown by the fact that hot-rolled Armco iron was strengthened 2500 lb. per sq. in. with a standard specimen and only 1600 lb. per sq. in. with a notched specimen. If the same ratio held for the 0.43-per-cent carbon steel, it might be expected that this steel would be strengthened 4300 instead of 6800 lb. per sq. in. On this basis the new endurance limit of the cast iron would be 13,600 lb. per sq. in.; the actual endurance limit found was 12,200 lb. per sq. in. This illustration is intended merely as a rough calculation to show what may be expected.

Comparing notched specimens of Armco iron and gray cast iron, it is clear why a considerable reduction of endurance limit due to the notch should be expected for Armco iron and much less for cast iron. Armco iron is a very homogeneous material and a square notch introduces high localized stress. The actual tests showed a reduction of endurance limit of 29 per cent. A square notch in gray cast iron would cause a reduction of endurance limit only if the localized stress due to the square notch is higher than that due to the carbon flakes. The actual tests showed no reduction of endurance limit due to the square notch.

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[1] *Bulletin No. 124*, Engineering Experiment Station, University of Illinois, 1921.

[2] *Bulletin No. 142*, Engineering Experiment Station, University of Illinois, 1924.

SUMMARY AND CONCLUSIONS

The above experiments on Armco iron and on gray cast iron lead to the conclusion that in an ordinary fatigue test there is usually a strengthening and a destructive process going on simultaneously. A homogeneous material like Armco iron develops a greater proportion of the maximum possible endurance limit than does a non-homogeneous material like gray cast iron. The reason for this seems to be that in Armco iron there are no large flaws like the carbon notches in gray cast iron, and in the race between the strengthening effect and the destructive effect, there is opportunity for the strengthening process to achieve results. With the gray cast iron, on the other hand, it is probable that the carbon notches produce concentrations of stress which prevent the strengthening process from being effective.

In under-stressing, as distinguished from an ordinary fatigue test, the Armco iron can be strengthened somewhat, but not a great amount, because even in the ordinary fatigue test, Armco iron is strengthened very considerably, as shown by the fact that the endurance limit is higher than the yield point. In under-stressing gray cast iron, the stress being below the endurance limit permits the strengthening process to take place because cracks are not being rapidly propagated. The strengthening process which was not effective before has now an opportunity to proceed, with the result that gray cast iron may be strengthened by very considerable percentages.

The following conclusions may be drawn:

1. For the gray cast iron tested the maximum strengthening due to under-stressing was obtained by about 15,000,000 cycles of stress. For numbers of cycles greater than this, there was no further strengthening.

2. For the gray cast iron tested, the most effective unit stress to produce strengthening due to under-stressing was one which was as close as possible to the original endurance limit. The maximum amount of strengthening obtained was 31 per cent.

3. Under-stressing hot-rolled Armco iron, using a standard fatigue specimen, produced about 10 per cent of strengthening.

4. Under-stressing hot-rolled Armco iron, using a specimen with a square notch, produced about 9 per cent of strengthening.

5. The presence of a square notch reduced the endurance limit of hot-rolled Armco iron by 29 per cent. A similar notch in gray cast iron produced no reduction of endurance limit.

6. A homogeneous material like Armco iron, in the ordinary fatigue test, seems to be able to develop a greater proportion of the

maximum possible endurance limit than a non-homogeneous material like gray cast iron. The result is that Armco iron cannot be strengthened very much more by under-stressing, while cast iron may be strengthened by considerable percentages.

Acknowledgment.—Thanks are due to H. Bornstein, of Deere and Co., for furnishing the cast-iron bars; to J. P. Butterfield, of the American Rolling Mill Co., for furnishing the hot-rolled Armco iron bars; and to J. A. Roesch, Jr., of the Steel Sales Corp., for furnishing the cold-drawn Armco iron bars, known as SS Magnetic Armco Ingot Iron.

DISCUSSION

Mr. H. F. Moore.[1]—I would like to add one word of discussion to Mr. Kommers' paper, not as a criticism but as a comment on the possible importance of this sort of study in one way which he did not mention. In our study of transverse fissures in rails now in progress, we have had to recognize the fact that one important property of steel seems to be one not defined at all today, that is the ability to withstand cold working without starting cracks. Obviously something of that kind happens in connection with the raising of the fatigue limit by under-stressing. Slip in cast iron can sometimes be detected under the microscope and I believe the ability to have the fatigue raised by under-stressing may have some connection with this ability to withstand cold working without starting fracture. I think this property will prove to be a property of very considerable importance, one about which we do not know much yet, and I commend the study of Mr. Kommers' paper in that connection.

Mr. Kommers (*author's closure by letter*).—Some of the practical applications involving under-stressing may be mentioned briefly:

1. It is evident that the operation of a new machine at light loads is desirable from the standpoint of permitting strengthening of parts to occur due to under-stressing.

2. Another field in which the phenomena of under-stressing must be taken into account is in the fatigue test itself. The practice of starting a fatigue test by stressing the specimen below the endurance limit, and then gradually increasing the stress by increments, which has been called "coaxing," may lead to erroneous results. Because of the strengthening which occurs during the under-stressing part of the test the endurance limit found in this way may be erroneously high. That is, a virgin specimen of this material would not have an endurance limit as high as that indicated by the test. This leads to the conclusion that fatigue tests on a series of specimens should start with stresses that cause failure. The stress on successive specimens should then be gradually reduced until a specimen is found which does not fail even after millions of cycles. The S-N diagram by becoming asymptotic to the N axis, usually indicates whether the endurance limit has been determined.

3. There is, on the other hand, a method in which "coaxing"

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[1] Professor of Engineering Materials, University of Illinois, Urbana, Ill.

seems to have a legitimate application. This is especially true of some of the non-ferrous metals in which the *S-N* diagram does not become asymptotic until 50 million, 100 million, or one billion cycles have been applied. In this method a series of specimens is tested at the higher stresses until the first part of the *S-N* diagram has been determined. Thereafter, when a specimen has been subjected, say, to 10 million cycles without failure, the unit stress is increased. If the specimen fails at the higher stress at a smaller number of cycles than a virgin specimen at the same stress, the assumption is that the original stress must have been above the endurance limit because the specimen was evidently damaged. If, on the other hand, the specimen at the higher stress withstands many more cycles than a virgin specimen at the same stress, the assumption would be that the first stress applied was below the endurance limit because the specimen had obviously been strengthened. Further use of this method will undoubtedly determine whether it may be used to advantage, and whether the conclusions drawn from it are correct.

FATIGUE TESTS OF FILLET WELDS

By R. E. Peterson[1] and C. H. Jennings[1]

Synopsis

In this paper, fatigue test data on fillet welds are given covering the effects of machining, spacing and size of weld. The tests were all made on rotating cantilever specimens 1 in. in diameter. A limiting size of weld was found, such that for a weld of larger size failure occurs through the parent metal at the base of the weld and for a weld of smaller size failure occurs through the weld metal. In the latter case, failure starts on the inside. It was found that the fatigue strength of a fillet weld could not be increased appreciably by machining a radius at the base of the weld. Spacing was found to reduce the fatigue strength considerably.

Introduction

The increasing use of welding in structures subjected to repeated stress[2] makes it necessary that research investigations be made on the fundamental properties of welded joints in fatigue. The results given in this paper are part of a fillet weld fatigue program in progress at the Westinghouse Research Laboratories. The results available to date cover work on the effects of machining, spacing and size of weld.

Test Details

All tests were made on specimens 1 in. in diameter, as shown in Fig. 1(*b*). The testing machine used for this investigation has been described in detail in a previous paper.[3] In preparing the specimens, three blanks were made for each specimen—one center blank and two similar end blanks are shown in Fig. 1(*a*). These blanks were turned from 2-in. diameter hot-rolled low-carbon steel (carbon 0.12 per cent, manganese 0.50 per cent, sulfur 0.02 per cent, and phosphorus 0.02 per cent). The blanks were tack-welded together while lined up in a jig consisting essentially of an angle in a horizontal position. The fillet weld was then completed with the specimen removed from the jig and held in a vertical position. The welds were made with $\frac{5}{32}$-in. diameter low-carbon uncoated electrodes (carbon 0.15 per cent, manganese 0.49 per cent, sulfur 0.03 per cent, phosphorus 0.02 per cent, silicon 0.02 per cent, and copper 0.07 per cent). The welding current was approximately 150 amperes in all cases.

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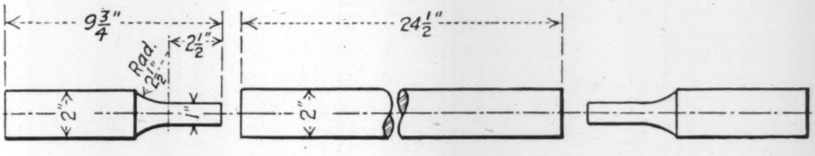
[1] Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

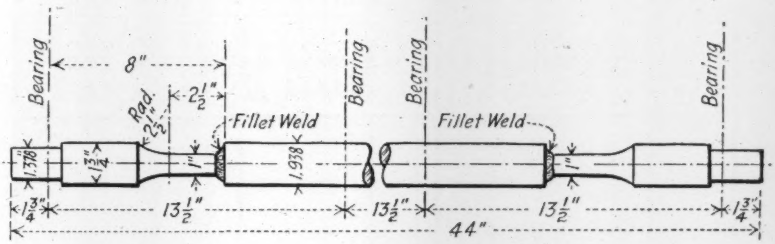
[2] M. Stone and J. G. Ritter, "Electrically Welded Structures Under Dynamic Stress," *Journal*, Am. Inst. Electrical Engrs., March, 1930, p. 202.

[3] R. E. Peterson, "Fatigue Tests of Large Specimens," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 371 (1929).

It was noticed that a number of the completed specimens vibrated excessively when set up in the machine for testing. After making a series of measurements it was concluded that the welds caused the specimens to warp during the interval between machining and testing. In order to obtain smooth-running test specimens, a portable lathe head (Fig. 3) was developed for turning the overhanging bearing ends to size in position. This successfully eliminated the vibration trouble so that the specimens ran very smoothly up to the time of the development of a fatigue crack. Incidentally, the lathe head is now being used on all of our large specimens, irrespective of whether they are welded or not.



(a) Blanks for Test Specimen (Prior to Welding)



(b) Completed Test Specimen.

FIG. 1.—Test Specimens

TEST DATA

The types of fillet welds tested are shown in Fig. 2. The test data are given in Table I and shown graphically in Figs. 6, 7 and 8. The stresses given are computed by applying the flexure formula to the 1-in. diameter section at the base of the weld, marked A–A in Fig. 2(a), regardless of the type of fracture. It should be pointed out that the stress computed in this manner is in no case the theo-

TABLE I.—FILLET WELD FATIGUE TEST DATA.

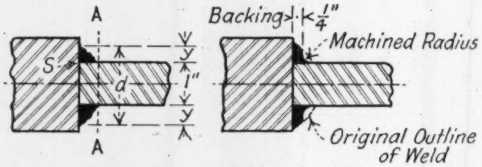
	Stress, lb. per sq. in.	Number of Cycles	Average Size of Weld, in.	Notes
SERIES A, NOT MACHINED (FIG. 2(A))				
No. 10.....	18 600	4 902 000	0.40	Failure at base of weld.
No. 11.....	23 200	523 000	0.43	
No. 12.....	18 100	10 159 000	....	No failure.
No. 13.....	21 900	1 138 000	....	Failure at base of weld
No. 14.....	20 700	2 675 000	0.44	
No. 16.....	18 600	3 413 000	0.44	
No. 17.....	26 800	512 000	0.44	
No. 18.....	30 400	201 000	0.43	
Endurance Limit....	18 500		Average 0.43	
SERIES AA, NOT MACHINED (CHECK TESTS 1½ YEARS LATER)				
No. 130-1..	18 400	4 400 000	0.43	Failure at base of weld.
No. 130-2..	19 100	1 650 000	0.42	
No. 131-1..	17 500	10 000 000	0.44	No failure.
No. 131-2..	18 700	10 000 000	0.41	
			Average 0.43	
SERIES B, NOT MACHINED (FIG. 2(A))				
No. 40-1...	25 200	268 000	0.31	Failure through weld metal.
No. 41-1...	23 600	627 000	0.32	
No. 41-2...	20 100	1 128 000	0.32	
No. 42-1...	19 000	1 916 000	0.27	
No. 42-2...	18 250	9 460 000	0.27	
No. 43-1...	19 500	1 739 000	0.31	
No. 43-2...	19 600	2 365 000	0.32	
Endurance Limit....	18 200		Average 0.30	
SERIES C, ⅛ IN. MACHINED RADIUS, ¼ IN. BACKING (FIG. 2(B))				
No. 45-2...	18 700	13 353 000	....	No failure.
No. 46-1...	21 800	2 272 000	....	Initial failure at surface normal to fillet. Fina failure inside by horizontal shear.
No. 46-2...	20 200	3 563 000	....	
No. 47-1...	27 000	784 000	....	
No. 47-2...	19 400	2 400 000	....	
Endurance limit.....	18 800			
SERIES D, ¼ IN. MACHINED RADIUS, ¼ IN. BACKING (FIG. 2(B))				
No. 49-1...	25 000	828 000	....	Initial failure at surface normal to fillet. Final failure inside by horizontal shear.
No. 49-2...	18 600	10 152 000	....	No failure.
No. 51-1...	21 800	463 000	....	Initial failure at surface normal to fillet. Final failure inside by horizontal shear.
No. 51-2...	20 500	469 000	....	
No. 52-1...	23 500	692 000	....	
No. 52-2...	20 200	651 000	....	
No. 53-1...	20 300	050 000	....	Initial failure at surface normal to fillet. No failure by horizontal shear.
No. 53-2...	19 400	10 138 000	....	No failure.
Endurance Limit....	19 500			
SERIES E, ⅜ IN. MACHINED RADIUS, ¼ IN. BACKING (FIG. 2(B))				
No. 57-1...	21 100	1 889 000	....	Initial failure at surface normal to fillet. No failure by horizontal shear.
No. 57-2...	19 400	10 578 000	....	No failure.
No. 58-1...	23 900	1 684 000	....	Initial failure at surface normal to fillet. No failure by horizontal shear.
No. 58-2...	22 400	195 000	....	
Endurance Limit....	19 700			

TABLE I.—*Continued.*

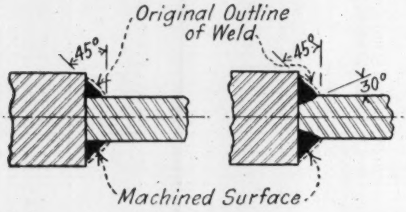
	Stress, lb. per sq. in.	Number of Cycles	Average Size of Weld, in.	Notes
SERIES F, NOT MACHINED, LARGE SIZE (AVERAGE 0.85 IN.) (FIG. 2(F))				
No. 79–1...	23 600	813 000	....	Failure at base of weld.
No. 81–2...	16 800	8 107 000	....	No failure.
No. 82–2...	19 600	2 456 000	....	Failure at base of weld.
No. 83–2...	18 100	2 536 000	....	
No. 85–2...	17 400	4 950 000	....	
No. 86–2...	18 500	2 521 000	....	
No. 88–2...	17 500	7 602 000	....	
No. 89–2...	21 900	1 465 000	....	
Endurance Limit....	17 000			
SERIES F_A, NOT MACHINED, LARGE SIZE (AVERAGE 0.85 IN.)[a]				
No. 133–2..	17 700	5 610 000	....	Failure at base of weld.
No. 134–2..	17 000	1 351 000	....	
No. 136–2..	16 750	5 261 000	....	
SERIES G, MACHINED 45 DEG., SHARP CORNER, 0.3 IN. SIZE (FIG. 2(C))				
No. 100–1..	19 300	824 000	....	Failure through weld metal.
No. 100–2..	16 900	1 994 000	....	
No. 101–1..	15 800	6 640 000	....	Failure at base of weld.
No. 101–2..	16 700	1 400 000	....	Failure through weld metal.
No. 103–1..	16 100	1 955 000	....	
No. 103–2..	15 600	4 004 000	....	
No. 105–1..	15 500	2 797 000	....	
No. 105–2..	14 900	4 827 000	....	
Endurance Limit....	14 700			
SERIES H, SAME AS SERIES G EXCEPT TAPERED PORTION AS SHOWN IN FIG. 2(D)				
No. 126–1..	14 500	10 000 000	....	No failure.
No. 126–2..	13 700	10 000 000	....	
No. 128–1..	15 500	1 735 000	....	Failure at base of weld.
No. 128–2..	17 300	646 000	....	
No. 135–1..	14 600	10 000 000	....	No failure.
No. 135–2..	15 100	10 000 000	....	
Endurance Limit....	15 200			
SERIES I, NOT MACHINED, $\frac{1}{32}$ IN. SPACE (FIG. 2(E))				
No. 110–1..	19 200	1 487 000	0.30	Failure at base of weld.
No. 110–2..	18 600	1 287 000	0.32	
No. 112–1..	16 200	2 491 000	0.34	
No. 112–2..	17 100	2 793 000	0.37	
No. 114–1..	14 800	3 543 000	0.32	
No. 114–2..	15 400	4 285 000	0.31	Failure not complete (cracked).
No. 116–1..	13 200	8 099 000	0.33	
No. 116–2..	12 000	15 396 000	0.33	
			Average 0.33	
SERIES J, NOT MACHINED, $\frac{1}{32}$ IN. SPACE (FIG. 2(E))				
No. 111–1..	15 100	1 612 000	0.25	Double fracture (Fig 5).
No. 111–2..	15 400	1 516 000	0.24	
No. 113–1..	14 400	2 208 000	0.23	
No. 113–2..	13 000	3 413 000	0.26	
No. 115–1..	11 700	13 240 000	0.28	No failure.
No. 115–2..	12 200	2 948 000	0.28	Double fracture.
No. 119–1..	11 800	2 088 000	0.23	
No. 119–2..	18 900	610 000	0.26	
			Average 0.25	

[a] Check test 8 months later.

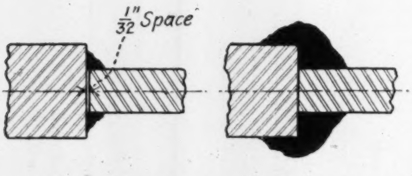
retically correct stress, because of stress concentration and because of the different types of failure. As given, however, all results are on a strictly comparative basis so far as moment-carrying capacity is concerned. It was apparent rather early in the investigation that the size of weld is of importance, particularly in determining the type of fracture. Measurements of weld size were therefore made in all cases. Four measurements (45 deg. apart) were made with calipers of dimension d, Fig. 2(a). Making use of the average of these four d measurements, the size of weld, y, was taken as $\frac{d-1}{2}$. The y values are entered in the tables to two decimal places, but from the fact that the weld contour is rather irregular some judgment must be used in the interpretation of the weld sizes.


A
S
d
y
1"
y
A
Backing
1/4"
Machined Radius
Original Outline of Weld

(a) Series A, B. (b) Series C, D, E.


Original Outline of Weld
45°
45°
30°
Machined Surface

(c) Series G. (d) Series H.



(e) Series I, J. (f) Series F.

FIG. 2.—Welded Ends of Test Specimens.

DISCUSSION OF RESULTS

Some rather interesting facts were discovered concerning the manner of failure in different sizes. If a comparatively large fillet weld is tested, fracture occurs at the base of the weld as is shown in Fig. 4(*a*). If, however, the amount of weld metal is reduced to 0.3 in. or less, failure occurs through the weld metal as shown in Fig. 4(*b*). The failure in such a case starts at the inside (*S* in Fig. 2(*a*)). The reason for this is that a high stress concentration exists at *S* which is virtually the end of a crack 1 in. long as seen in axial section Fig. 2(*a*). An interesting fracture is shown in Fig. 5, representing (fortuitously) a weld of such size as to be equally strong through the weld metal and through the parent metal at the base, so that both types of fracture progressed simultaneously, the final fracture occurring by horizontal shear. In series G, failure started at the inside. In series H, everything was kept the same as in series G except that the end blank was made as shown in Fig. 2(*d*), which decreased the stress at the inside considerably. This caused the failure to occur

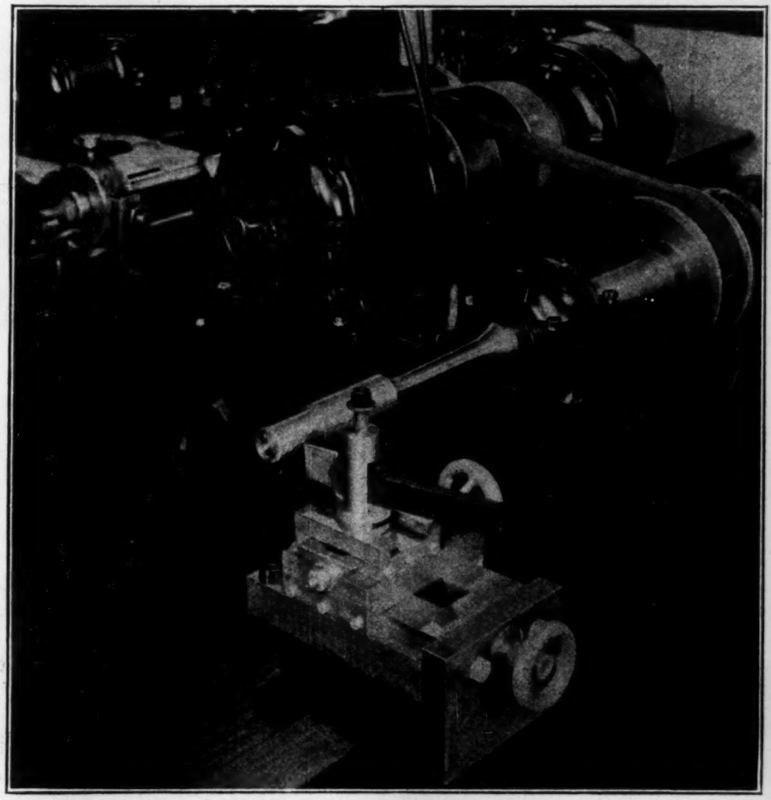
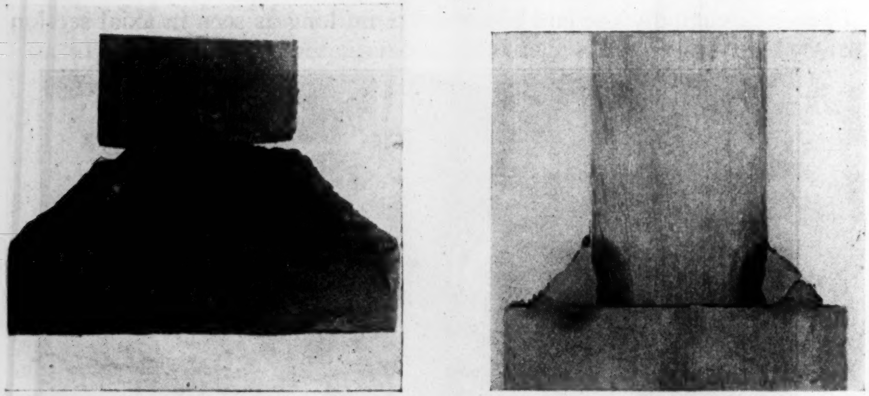


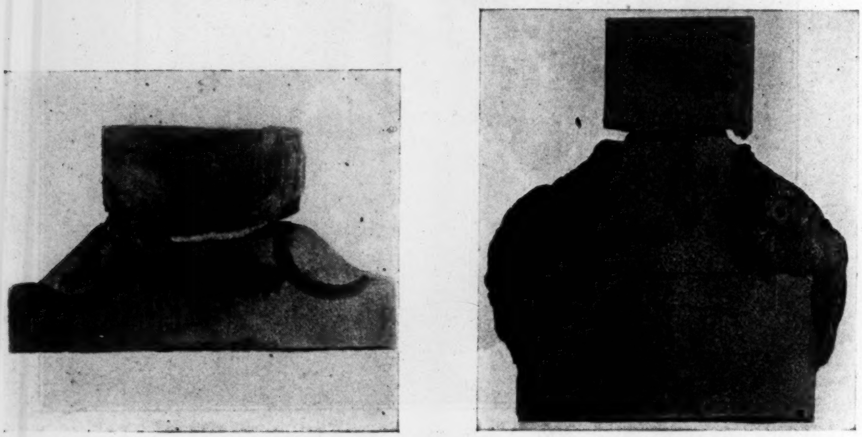
FIG. 3.—Portable Lathe Head.

at the base of the weld. There is not a great difference in endurance limits in the two cases.

The effect of various machined radii is shown in Fig. 6. The motive which prompted this phase of the work was that a strengthening effect was anticipated by replacing the ragged sharp corner (Fig. 2(*b*)) with a machined radius and thereby reducing stress concentration. It is seen from Fig. 6 that machined radii are considerably stronger than a machined sharp corner. However, a comparison of these values with the unmachined specimens (Fig. 7) shows no advantage in machining. The reason for this is not clear, but is



(*a*) Series A. (*b*) Series B.



(*c*) Series G. (*d*) Series F.

FIG. 4.—Fractured Specimens.

apparently tied up with the residual stress question, which is of prime importance in welded joints.

The effect of size is shown in Fig. 7. If the weld is made about 0.3 in., failure occurs through the weld metal and for smaller sizes a reduction of strength would obviously occur. For sizes greater than 0.3 in., failure occurs at the base through the parent metal, so it would be expected that the strength would no longer depend on size. However, a small reduction of strength was obtained for large welds. Here again the reason is not obvious, but some difference may be due to heating effect and residual stress. It should be borne in mind that in all failures occurring at the base of the weld, the fracture begins in a fused area (Fig. 4(*c*)) and not in the parent metal proper. The reduction of strength due to large size is apparently a real effect, since similar results have been obtained with butt welds.

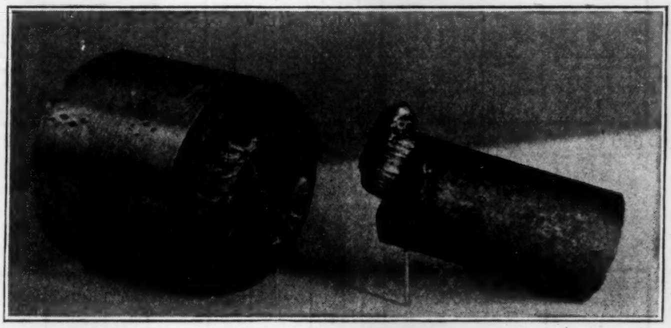


FIG. 5.—Double Fracture.

The effect of spacing is shown in Fig. 8, a considerable reduction of strength being obtained. Some of this effect is undoubtedly due to the fact that the section modulus is somewhat reduced by separating the two bars which when butted tight are capable of carrying compressive stresses. The double type of fracture previously described (shown in Fig. 5) was also obtained in these tests.

CONCLUSIONS

1. Either of two types of failure occurs in fillet welds: failure at the base (section *A–A* in Fig. 2(*a*)) or failure through the weld metal.

2. There is a limiting size at which failure occurs both ways simultaneously, in this case 0.3 in. (*y* dimension in Fig. 2(*a*)).

3. For sizes below the limiting value, failure will occur through the weld metal with lower effective strength.

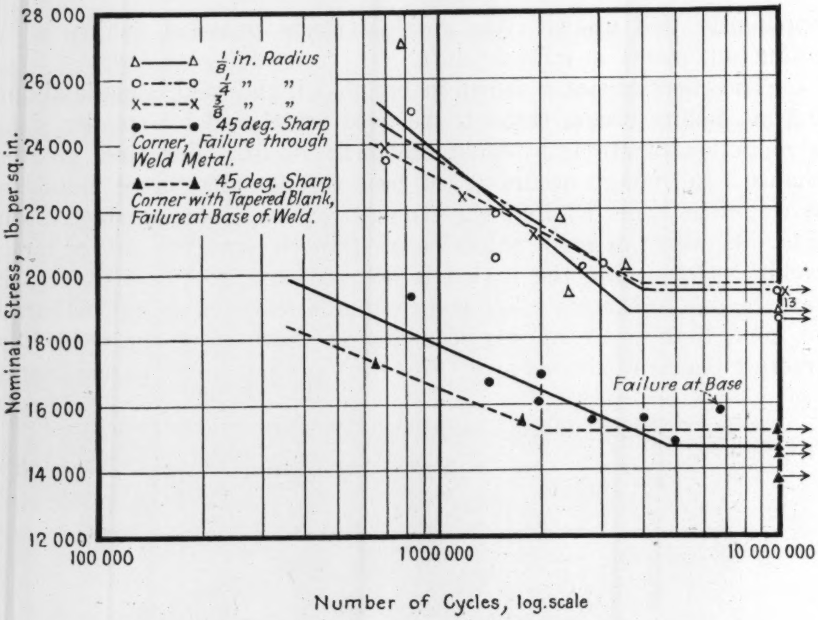


FIG. 6.—Showing Effect of Machining.

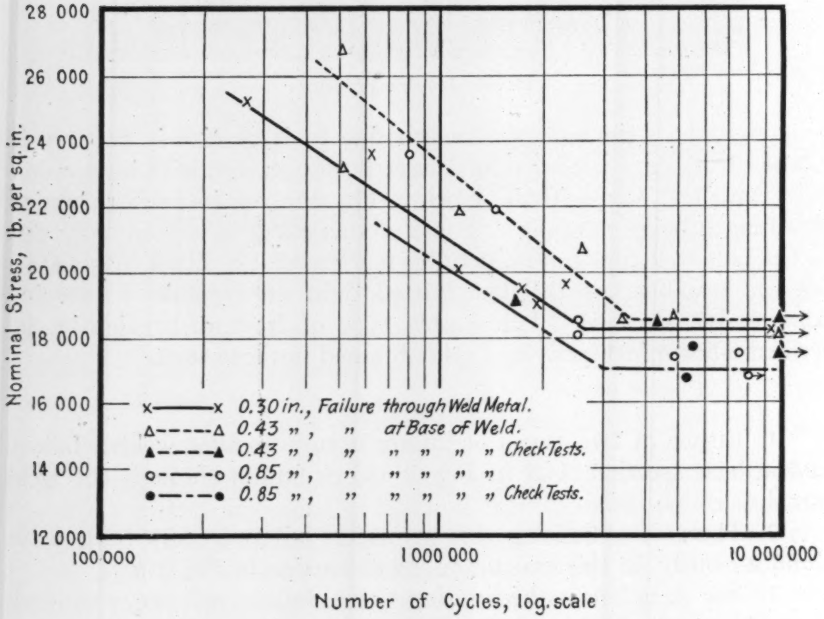


FIG. 7.—Showing Effect of Size of Fillet Weld.

4. For sizes above the limiting value, failure will occur at the base of the weld, with the strength remaining substantially the same except for comparatively large welds where a small reduction of strength may be expected.

5. Where failure occurs through the weld metal, the fracture starts at the inside.

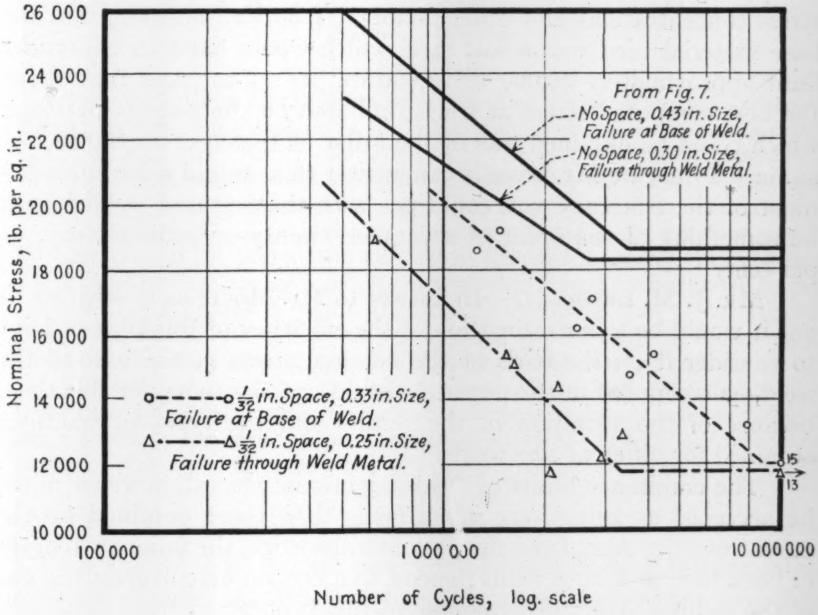


FIG. 8.—Showing Effect of Spacing.

6. A fillet weld is not appreciably strengthened by machining a radius at the base of the weld.

7. The effect of spacing is to reduce the strength of the fillet weld considerably.

Acknowledgment.—The authors have been assisted by Mr. F. C. Cassel in the operation of the testing machine. Particular acknowledgment is due Mr. J. M. Lessells, Manager of Mechanics Division, for his interest and suggestions concerning the investigation.

DISCUSSION

Mr. H. F. Moore.[1]—I notice that the authors state, quite correctly, that the computed stresses are purely nominal in value, through stress concentrations and other factors. I notice, however, that the base material used was a soft steel which would have an endurance limit approximately 26,000 to 28,000 lb. per sq. in., and that about the best computed stress at fracture, based on the size of specimen, which could be obtained was of the order of 16,000 or 17,000 lb. per sq. in. I imagine Mr. Lessells can answer this: would a fair measurement of the efficiency you could get with that type of welded joint be something of the order of seventeen twenty-sevenths or, say, 65 per cent?

Mr. J. M. Lessells.[2]—In answer to Mr. Moore as to whether or not it would be a fair estimation of the efficiency of this type of joint to consider it on the basis of the nominal stress at the base of the weld, as computed in the paper, I should not like to say at this time, because of the variation in the results and the types of fractures obtained for different size welds.

The endurance limits of welded joints in general, however, must be accepted as being very much lower than those obtained for the parent metal. Also, from the present knowledge, the fatigue strengths of both fillet and butt welds depend to a certain extent upon the size of the welds. A marked example of this is obtained from large butt welds where endurance limits of less than one-half those of the parent metal are obtained.

Messrs. R. E. Peterson[3] and C. H. Jennings[3] (*authors' closure by letter*).—Mr. Moore has proposed a "fatigue efficiency" value for the fillet welded joint. Such a value has a logical basis, even though the stresses are not definitely known because of stress concentration. As pointed out in the paper, all results can be considered comparative so far as moment-carrying capacity is concerned. In other words, the fillet welded joint as described in the paper (series A) will carry only 65 per cent as much alternating bending moment as the parent metal without stress concentration. Such an efficiency value is therefore justifiable and should be of practical value.

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[1] Professor of Engineering Materials, University of Illinois, Urbana, Ill.

[2] Manager, Mechanics Division, Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[3] Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

FATIGUE STUDIES OF TELEPHONE CABLE SHEATH ALLOYS

By J. R. Townsend[1] and C. H. Greenall[2]

Synopsis

This paper is a continuation of a previous paper presented before the Society by one of the authors in 1927[3] and further discusses results of fatigue studies of lead sheath for telephone cables. The results of the investigation of the fatigue characteristics of lead cable sheath alloys using the rotating-beam type fatigue machine are reported. Data are also given for static fatigue.

The failure of lead cable sheath alloys as reported in the previous paper is by intergranular fracture and in the case of the lead-antimony alloys repeated stress appears to reduce the solubility of antimony in lead. The type of fracture observed for the rotating beam specimens is similar to that of the repeated flexure specimens described in the previous paper. The type of failure on the static fatigue test is a breaking down of the bond between the crystals.

The fatige properties of the 0.04-per-cent calcium-lead alloy described in this paper is by intergranular fracture, but there is no loss of solid solubility of the calcium in the lead. Great improvement in the fatigue endurance was noted for an alloy of the same tensile properties as the lead-antimony alloy.

Introduction

In the previous paper[3] the type of intergranular fatigue failure which occurs in aerial telephone cable sheath alloy was described. It was explained that this failure was due to a combination of vibration produced by road shocks transmitted through the supporting structure, to the action of the wind and to repeated bending caused by daily and seasonal changes in temperature. The coefficient of expansion of lead cable is 60 per cent greater than that of the supporting strand. This causes the cable to elongate more than the strand and produces bowing at the poles where the supporting strand is secured. The improvement of a 1-per-cent antimony, balance lead cable sheath alloy over pure lead cable sheath was demonstrated in the previous paper. In this present paper an alloy which is a further improvement from the standpoint of fatigue consists of nominally 0.04 per cent calcium, balance lead. All results given in this paper were obtained from laboratory tests. Data from field tests which are now in progress will, of course, be the final criterion for evaluating the usefulness of these materials for practical purposes.

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[1] General Development Laboratory, Bell Telephone Laboratories, Inc., New York City.

[2] Member of Technical Staff, Bell Telephone Laboratories, Inc., New York City.

[3] J. R. Townsend, "Fatigue Studies of Telephone Cable Sheath Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part II, p. 153 (1927).

Test data on the fatigue testing machine employing a flat cantilever specimen as described in the previous paper are given herewith for the various materials tested. In addition a rotating beam machine (also cantilever type) was developed similar to the type described by McAdam.[1] A new type of rotating-beam fatigue specimen was developed which is relatively inexpensive to manufacture and produces satisfactory results.

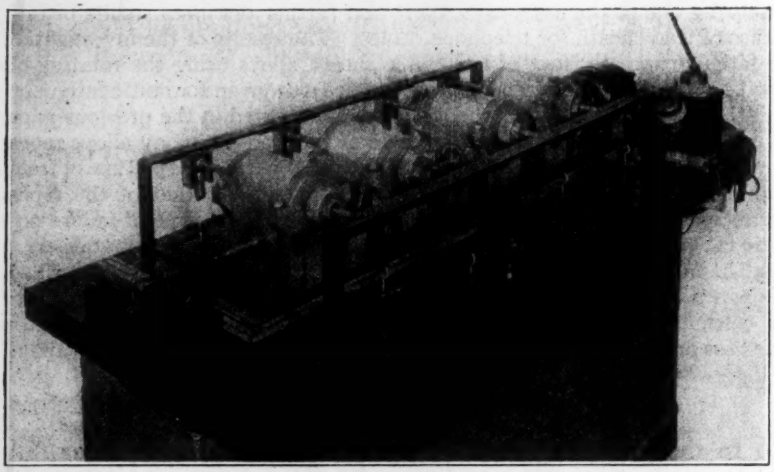

FIG. 1.—Rotating Beam Fatigue Machine.

Static fatigue tests were made to determine the rate of flow of cable sheath materials under steadily applied load. The type of fracture which occurs is interesting in that it shows that the failure is caused by grain separation.

TESTING MACHINES AND SPECIMENS

Flat Cantilever Beam Fatigue Tests:

As described in the previous paper,[2] the fatigue testing machine consists of a cam rotating at 700 r.p.m. The specimen is a flat cantilever beam so designed as to give uniform bending moment for a length of $\frac{1}{4}$ in. and about $\frac{1}{2}$ in. from the clamped area and has a free length of approximately 3 in. (See previous paper, Fig. 7.) The cam is deflected 0.11 in., corresponding to a calculated stress of 1350 lb. per sq. in. for the lead-antimony alloy. The machine mounts 56 specimens all of which are stressed the same. The machine in reality is a repeated strain machine, since the deflection of the specimen is caused to follow the cam at all times by means of a helical compression spring which holds the end of the test specimen against the rotating cam.

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[1] D. J. McAdam, Jr., "Endurance of Steel Under Repeated Stress," *Chemical and Metallurgical Engineering*, December 14, 1921, p. 1081.

[2] *Loc. cit.*

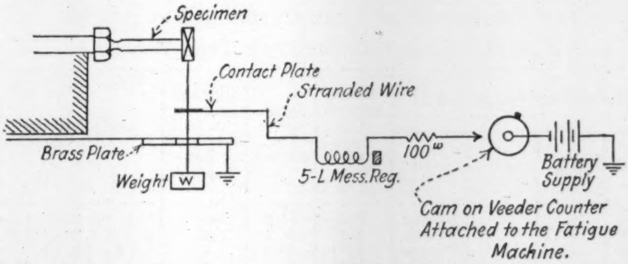
Specimen
Contact Plate
Stranded Wire
Brass Plate
Weight
W
5-L Mess.Reg.
100 ω
Battery Supply
Cam on Veeder Counter Attached to the Fatigue Machine.

FIG. 2.—Schematic Diagram of Monitoring Circuit for Rotating-Beam Fatigue Machine.

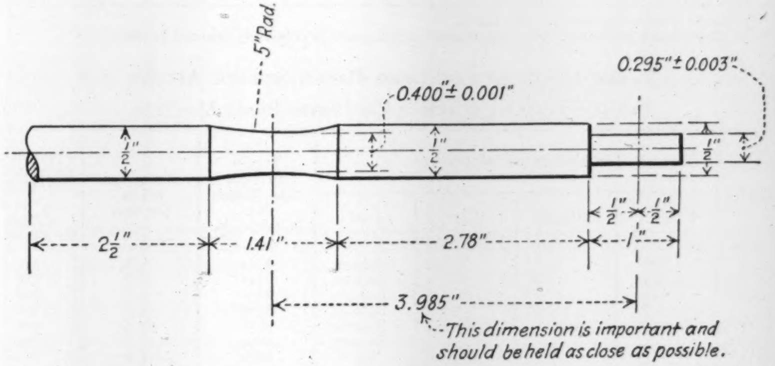
5" Rad.
0.400"± 0.001"
0.295"± 0.003"
1/2"
1/2"
1/2"
1/2"
1/2"
2 1/2"
1.41"
2.78"
1"
3.985"
This dimension is important and should be held as close as possible.

FIG. 3.—Rotating-Beam Fatigue Specimen, as Devised for Lead Alloys.

This machine is intended to compare various cable sheath alloys at what is considered to be a severe service stress condition. Comparison of the various alloys is obtained by determining the number of deflections to failure. By using this test as a preliminary survey of the fatigue characteristics of various proposed alloys, those which show considerable promise may be selected for further fatigue tests including the determination of the endurance limit. This procedure saves considerable time in that the comparative performance of a number of alloys may be determined within a limited period. To determine the endurance limit for a large number of alloys is a very time-consuming process.

This type of machine is open to the objection that the relative fatigue resistance of two alloys may be different at different stresses. There is a possibility of this in comparing widely dissimilar metals; but so far as our experience with lead alloys is concerned this has not been found to be the case. This machine is also very useful in detecting the effect of small amounts of impurities and in this regard it is much more sensitive than the tension test. Arsenic impurity of the order of 0.001 per cent can be detected on this machine but not on the tension test.

TABLE I.—TESTS OF LEAD CABLE SHEATH ALLOYS.
Fatigue Tests in Flat Cantilever Type Machine.

Alloy[b]	Chemical Analysis, per cent				Tensile Strength (One Month Old), lb. per sq. in.	Elongation in 2 in., per cent	Rockwell Hardness, $\frac{1}{4}$-in. Ball, 30-kg. Load (Red Figures)	Fatigue Resistance (One Month Old), millions of cycles
	Calcium	Antimony	Tin	Lead				
No. 1	0.041	....	....	Balance	3290	41.0	47	18.6, 28.9, 51.4[a] (4 specimens)
No. 2	0.040	....	....	Balance	2790	37.5	45	29.4, 57.4, 28.9, 142.4[a] (2 specimens)
No. 3	0.040	....	....	Balance	2870	40.0	39	4.6, 8.4, 5.6, 9.5.
No. 4	0.040	....	....	Balance	3677	44.0	40	74.6, 12.9, 16.6, 168.7[a]
No. 5	0.042	....	....	Balance	3075	44.0	36	32.5, 45.5, 97.4, 136.9[a]
No. 6	....	....	....	100	1861	57.7	..	1.3, 0.47, 0.96, 0.53, 0.30, 0.53, 0.53
No. 7	....	1.00	....	Balance	2952	37.6	..	1.81, 1.81, 2.16, 2.59, 1.99, 2.45

[a] Specimens removed unbroken at this point.
[b] The alloys tested were prepared by Schumacker and Bouton[1] as previously reported by them.

TABLE II.—TESTS OF LEAD CABLE SHEATH ALLOYS.
Fatigue Tests in Rotating Cantilever Beam Machine.

Alloy[b]	Chemical Properties, per cent				Tensile Strength (One Month Old), lb. per sq. in.	Elongation in 2 in., per cent	Approximate Endurance at 50 000 000 Cycles of Stress, lb. per sq. in.
	Calcium	Antimony	Tin	Lead			
No. 8	0.039	....	..	Balance	3184	72.5	840
No. 9	0.038	....	..	Balance	2713	72.9	660
No. 10	0.038	....	..	Balance	3462	61.0	685
No. 11	.....	1.00	..	Balance	3200[a]	36.0[a]	450
No. 12	.....	1.00	..	Balance	3995	40.5	420
No. 13	.....	1.00	..	Balance	2765	57.5	300[a]
No. 14	.....	....	..	100.0	2084	91.8	215

[a] Estimated.
[b] The alloys tested were prepared by Schumacker and Bouton[1] as previously reported by them.

Rotating Cantilever Beam Tests:

In order to obtain results on as many specimens as possible and at a minimum of testing cost the McAdam type of rotating cantilever beam machine was selected. Figure 1 shows the arrangement of one

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[1] E. E. Schumacker and George Bouton, "Age Hardening of Lead-Calcium Alloys," *Metals and Alloys*, March, 1930, p. 405.

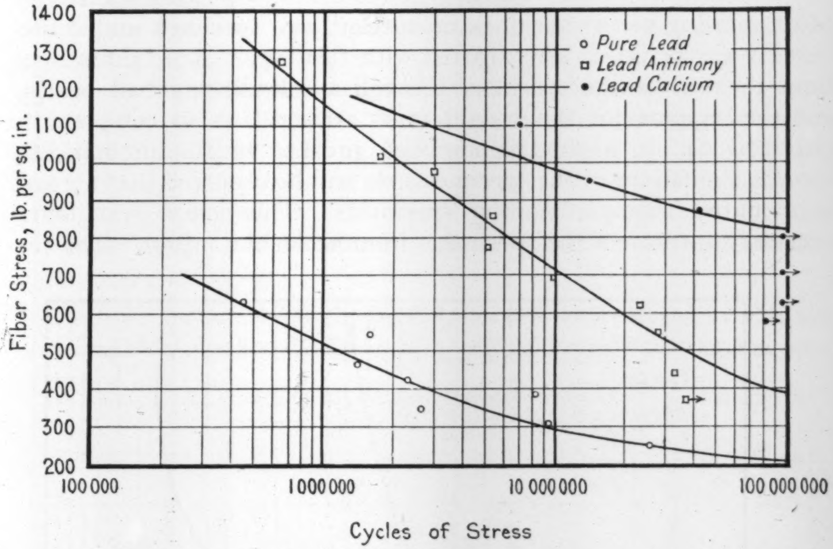

FIG. 4.—Stress-Cycle Endurance Curves for Pure Lead, Lead-Antimony and Lead-Calcium Cable Sheath Alloys.

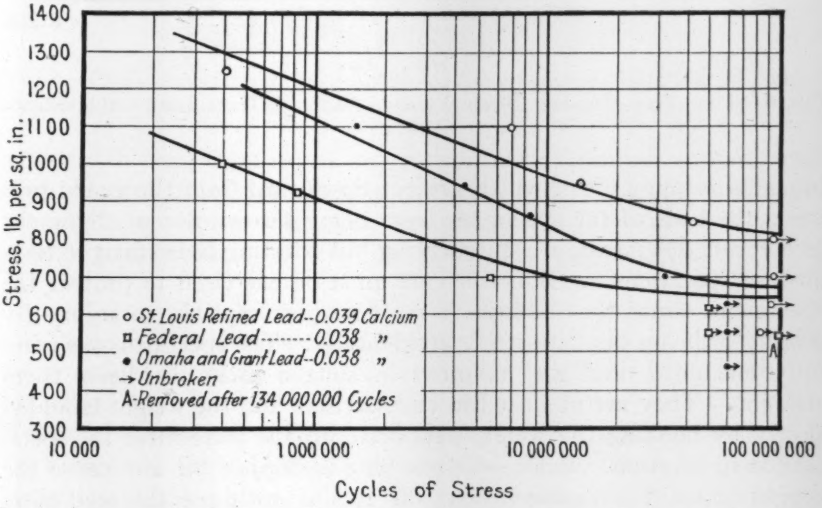

FIG. 5.—Stress-Cycle Endurance Curves for Lead-Calcium Cable Sheath Alloys.

of the two machines made available for this work. The machine consists of eight chucks which grip the cantilever beam specimens. Most rotating-beam machines mount but one specimen and consequently are inefficient as compared with this type. A weight is hung from the end of the specimen through a self-aligning ball bearing and the support for the weight is so arranged as to complete an electrical circuit when the specimen breaks, which automatically records the failure of the specimen. It will be observed that a guard is mounted surrounding the specimens. This guard was found necessary to protect the specimens from accidental injury. The two

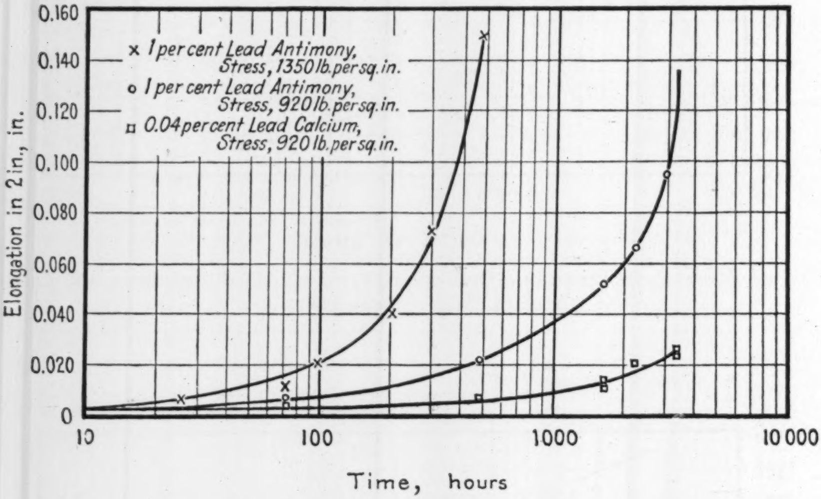

FIG. 6.—Long-Time Tension (Static Fatigue) Tests of Three Lead Cable Sheath Alloys.

brackets forming a slot which project downward from the guard prevents the ends of the specimens from being thrown out of alignment as a result of vibration. In carrying out rotating beam fatigue tests on lead specimens, considerable care must be exercised to protect the specimens, since the material is soft and susceptible to injury by scoring or being bent if struck accidentally. The specimens are carefully machined and are mounted in slotted racks to keep them straight. They are mounted in the machine and the weight is added slowly by hooking the weight support onto the yoke after the specimen is in rotation. Before the machine is stopped for any cause the weights must be removed first. If this is not done the lead alloy might take a permanent set due to creep, which would ruin the specimen for further use. Figure 2 shows a schematic diagram of the monitoring circuit for this machine.

Figure 3 shows the design of the rotating-beam fatigue test specimen. A 5-in. radius is cut into a ½-in. diameter extruded round rod by mounting the rod on the lathe and using a profile milling cutter mounted on a swivel head. The milling cutter is moved through a radius of 5 in. thus profiling the reduced section of the specimen. The end of the specimen is turned down to fit a convenient size of self-aligning ball bearing. The cost of preparing specimens in this way is very slight and reduces the milling operations to a minimum.

Static Fatigue Tests:

In order to determine the performance of lead cable sheath alloys under steadily applied load, tension test specimens having an 8-in. gage length were clamped at one end on a vibrationless support and a suitable weight was attached to the other end. The flow or elongation of the specimen with time was observed by means of a cathetometer to an accuracy of 0.002 in. in the 8-in. gage length.

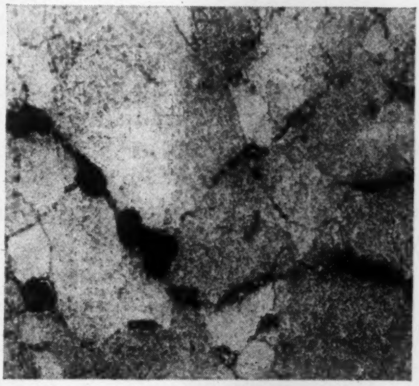

FIG. 7.—Photomicrograph of Lead-Antimony Alloy Showing Voids Due to Failure in Long-Time Tension Test. Etched with Acetic Acid and Superoxyl (× 120).

RESULTS OF FATIGUE TESTS

Table I gives the chemical composition and physical properties of the various alloys investigated on the flat cantilever type machine. The alloys were extruded in the form of tape 1½ in. wide and ⅛ in. thick, and the extrusion forces and temperatures are also given.

Similarly, Table II gives the chemical composition and physical properties of the various alloys investigated on the rotating beam fatigue machine. The extrusion temperatures and pressures are also given. Figures 4 and 5 show the results of the fatigue endurance tests on the various alloys on the rotating beam machine; the endurance limits appear in Table II.

The results of the static fatigue tests for three alloys are shown in Fig. 6. Figure 7 is a photomicrograph of a broken specimen of the lead-antimony sheath material and shows that the static fatigue failure is due to grain separation.

DISCUSSION

The marked superiority of the lead-calcium alloys in resistance to fatigue and also from an endurance limit standpoint is demonstrated. Whereas there is only a slight difference in the tensile strength and hardness of the lead-antimony and lead-calcium alloys, it will be observed that there is a great improvement in the fatigue endurance. The nominal 0.04-per-cent calcium-lead alloy which has been described elsewhere[1] is considered remarkable in view of the hardening action of a small amount of calcium and the great improvement in fatigue endurance over the lead-antimony alloy of approximately the same tensile properties. Microscopic examinations which have been reported elsewhere[2] show that the lead-calcium alloy is stable and does not exhibit the type of failure previously reported for the lead-antimony alloy. The static fatigue tests reported herewith and also reported elsewhere[2] show that the lead-calcium alloy does not exhibit the grain boundary weakness demonstrated by the lead-antimony cable sheath alloy.

CONCLUSIONS

The investigation of fatigue properties of lead cable sheath alloys has demonstrated that fatigue failure is by means of intergranular fracture. The method of using a flat cantilever type fatigue machine, wherein alloys for a particular purpose are all compared under repeated strain conditions, is a satisfactory method of making a preliminary survey of the field. The rotating beam fatigue test for lead alloys shows the remarkable effect of small additions of alloying elements with lead on the fatigue properties. The improvement of the 0.04-per-cent calcium-lead alloy over the lead-antimony alloy from a fatigue standpoint is marked, without corresponding changes in tensile strength or hardness. The static fatigue tests also show the superiority of the lead-calcium over the lead-antimony alloy.

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[1] E. E. Schumacher and George Bouton, "Age Hardening of Lead-Calcium Alloys," *Metals and Alloys*, March, 1930, p. 405.

[2] R. S. Dean and J. E. Ryjord, "Alloys for Cable Sheathing," *Metals and Alloys*, March, 1930, p. 410.

DISCUSSION

MR. G. O. HIERS[1] (*presented in written form*).—This paper and others prior along similar lines give valuable information which is not only applicable to telephone cable design but also to power cable and to the use of lead sheet and pipe for constructional purposes and for chemical equipment.

MR. J. B. KOMMERS[2] (*presented in written form*).—It seems to me that the authors are correct in looking upon the machine using flat specimens as a means merely of a preliminary survey. The long-time tension tests show that considerable permanent deformation takes place at a unit stress of 1350 lb. per sq. in., and it is quite probable that a constant-strain machine for a material like lead does not produce conditions of constant stress. On this account there would always be considerable uncertainty in trying to interpret results from such a test.

The authors, therefore, quite properly make further fatigue tests on a rotating beam machine, in which weights are used to produce a condition of constant stress. From these tests the endurance limit may be determined or estimated fairly closely, giving a result which has a definite meaning.

I should like to ask the authors a number of questions:

1. What speed is used on the rotating-beam machine?
2. Does the rotating-beam specimen receive any polishing?
3. What means are employed for getting a constant source of power, so that the rotating-beam machines will not stop at intervals?

MR. H. F. MOORE.[3]—In connection with the fatigue testing of lead, it will be necessary to consider the tendency of the lead to *flow*. In the Materials Testing Laboratory of the University of Illinois there are going on long-time steady load tests of lead and lead alloys, and already there has been obtained evidence of flow of lead and some lead alloys at room temperature under stresses as low as 400 lb. per sq. in.

MR. J. R. TOWNSEND.[4]—Replying to the question raised by Mr. Kommers, on the rotating-beam machine, a speed of 700 r.p.m. was used. The reason for selecting this speed was that it was a convenient one. At higher speeds we had vibration in our machine and liability of damaging the specimen.

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[1] Chemist, National Lead Co., Research Laboratories, Brooklyn, N. Y.

[2] Professor of Mechanics, Engineering College, University of Wisconsin, Madison, Wis.

[3] Professor of Engineering Materials, University of Illinois, Urbana, Ill.

[4] General Development Laboratory, Bell Telephone Laboratories, Inc., New York City.

The specimens were not polished, but they represent a very fine machined surface. After the specimens were cut to shape, they were carefully finished by the tool. The reason we did not attempt to polish the specimens was because we felt that any polishing would cause serious defects, such as surface flow of the metal, which might invalidate our results In addition, the friction of polishing to a certain extent might affect the grain size or anneal of the material on the surface. Lead, as you know, is a material that is subject to grain growth and annealing action at atmospheric temperatures

As regards the constant source of power, we have, in our laboratory, a motor generator set which is fed directly from the New York power system. This motor generator set is, in turn, used to supply constant voltage to direct current motors that are used on the fatigue testing machines. The motor generator set has no automatic control on it, but inasmuch as a light load is used and it is under constant supervision, we believe that the speed is reasonably constant.

MR. BRINLEY JONES[1] (*by letter*).—The effect of small amounts of calcium on the fatigue strength of lead is very striking when considered in relation to the static properties of these alloys. It would be interesting to know the effect of calcium, if any, on the corrosion resistance of lead.

The writer must confess that his chief interest lies in the successful application of the cheap and expeditious rotating cantilever type of test to cable sheathing alloys.

Reference is made in the paper to the gradual loading and unloading of specimens while rotating. It is known that lead responds elastically to very rapidly applied loads. One might expect, therefore, that the fatigue ranges of lead alloys would depend to some extent on the frequency of stress applications. It would be a comparatively simple matter to clear up this point—which is of considerable practical importance—by means of the testing machine described in the paper.

MR. TOWNSEND (*author's closure by letter*).—Replying to comments made by Mr. Jones, small amounts of calcium have no practical effect on the corrosion resistance of lead. Indeed, the corrosion resistance of pure lead and lead-calcium alloy are the same for all practical purposes.

It is true that lead has different fatigue ranges depending upon the frequency of the stress application. For the purposes of the tests in mind a convenient frequency of stress application was selected. The essential thing is that the character of the fatigue break which occurs on the fatigue testing machine be exactly similar to the type of fatigue fracture that occurs on cables in service. The practical objective of the work covered by this paper was to reproduce in the laboratory the type of fatigue fracture that occurs in service.

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[1] Technical College, Bradford, England.

It is our belief that after a certain stress is reached the frequency of application of the load has very little if any effect. In other words, if the elastic range is exceeded, regardless of the frequency, the type of fracture that results is different from that which is experienced in service. It is not believed proper to add the effect of plastic deformation to fatigue failure which is a phenomenon that occurs within the apparent elastic range of the material.

A NOTE ON FATIGUE TESTS OF NITRIDED STEEL

By N. L. Mochel[1]

Synopsis

In this note, fatigue test data on chromium-aluminum-molybdenum steel, before and after hardening by the nitriding process, are given. The tests were made on rotating cantilever specimens. Data are also given as to the chemical composition and the tension, impact and hardness characteristics of the material used.

Introduction

During the past several years, much valuable data have been published regarding the nitriding of steel and the physical properties of such steels. There have been few data published as to the endurance properties of nitrided steels. In a recent publication[2] appears the statement that "while no laboratory tests have as yet been carried out on this subject in this country, European tests indicate an unusually high resistance on the part of nitrided sections to alternating stresses, and service tests on parts of this kind in America confirm this statement." In a recent symposium devoted to the subject of nitriding,[3] a vast amount of data was presented, but none relative to the endurance properties of the materials were included.

Such information is very necessary in the application of nitrided steels for many purposes. Some tests were made at the South Philadelphia Works of the Westinghouse Electric and Manufacturing Co. during the past year, to determine the endurance limit of a commercial steel after nitriding. These results are presented at this time, with the hope that they may be of interest to many, and that discussion may be provoked that will bring forward the results of other tests that no doubt have been carried out.

Material and Test Methods

Three bars, $1\frac{1}{16}$ in. round, of chromium-aluminum-molybdenum steel of commercial grade, selected at random from a larger lot, were used in the investigation. Disks were cut from each end of the bars, and etched in hot 50-per-cent HCl solution, and revealed a uniformly sound and clean condition of the steel.

---

[1] Metallurgical Engineer, Westinghouse Electric and Manufacturing Co., Philadelphia, Pa.

[2] "Nitralloy and the Nitriding Process," Ludlum Steel Co., 1929.

[3] "Nitriding Symposium," Special Edition, *Transactions*, Am. Soc. Steel Treating, Vol. XVI, No. 5, October, 1929.

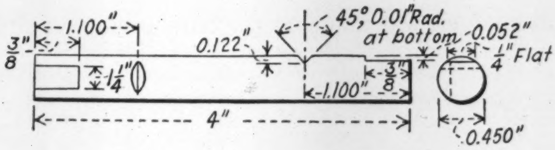
1.100"
3/8"
1 1/4"
0.122"
45°, 0.01" Rad. at bottom
0.052"
1/4" Flat
3/8"
1.100"
4"
0.450"

FIG. 1.—Impact Test Specimen.

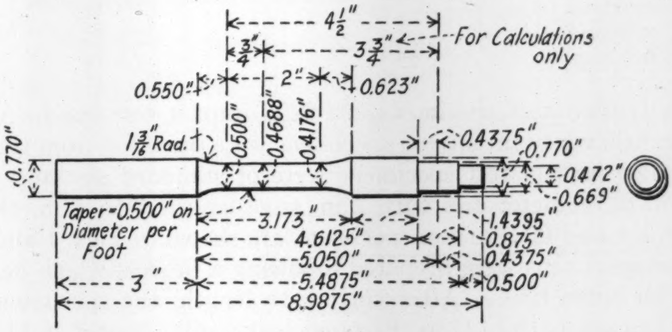
4 1/2"
3/4"
3 3/4"
For Calculations only
0.550"
2"
0.623"
1 3/16" Rad.
0.500"
0.4688"
0.4176"
0.770"
0.4375"
0.770"
0.472"
0.669"
Taper = 0.500" on Diameter per Foot
3.173"
4.6125"
5.050"
1.4395"
0.875"
0.4375"
3"
5.4875"
0.500"
8.9875"

FIG. 2.—Fatigue Test Specimen.

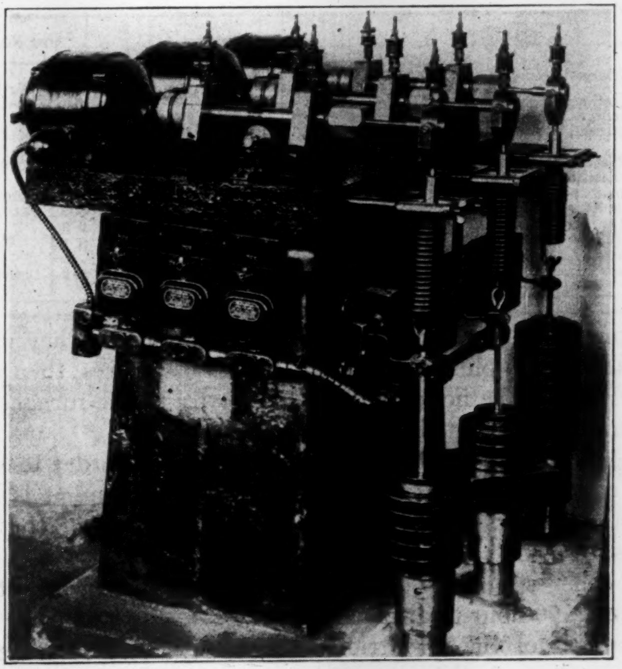

FIG. 3.—Fatigue Testing Machine.

Chemical analysis was made on the bars, giving results as follows:

Carbon	0.35 per cent
Manganese	0.54 "
Phosphorus	0.014 "
Sulfur	0.012 "
Silicon	0.220 "
Nickel	0.20 "
Chromium	1.67 "
Aluminum	0.91 "
Molybdenum	0.20 "

Six tension test specimens, six Izod impact test specimens and thirty cantilever beam fatigue specimens were prepared from the three bars. The tension test specimens were of standard size and shape, 0-505 in. in diameter and with 2 in. gage length with $\frac{3}{4}$ in. threads. The impact and fatigue test specimens are shown in Figs. 1 and 2.

The specimens were prepared following a process which has been in use for some time. After cutting to length, the specimens were heated in a salt bath to 1750° F., quenched in oil, reheated to 1100° F., held for one hour, and cooled slowly in the furnace. They were then rough machined to plus 0.020 in. of size on all surfaces, then annealed at 1000° F. for three hours, and cooled slowly in the furnace. They were then finish machined.

TABLE I.—RESULTS OF TESTS ON NITRIDED STEEL.

	Before Nitriding			After Nitriding		
	Bar A	Bar B	Bar C	Bar A	Bar B	Bar C
Proportional Limit, lb. per sq. in.	72 000	72 000	71 000	......	......	......
Johnson Elastic Limit, lb. per sq. in.	119 000	124 000	120 000	......	......	......
Yield Point:						
0.2 per cent Plastic Deformation, lb. per sq. in.	142 700	142 500	140 100	......	......	......
0.5 Per cent Total Deformation, lb. per sq. in.	135 300	135 000	133 400	......	......	......
Drop of Beam, lb. per sq. in.	150 500	149 250	147 250	138 500	140 000	143 000
Tensile Strength, lb. per sq. in.	162 500	162 500	159 750	161 000	163 750	162 000
Elongation in 2 in., per cent	15.5	16.5	15.5	6.0	5.0	7.0
Reduction of Area, per cent	49.2	48.9	48.6	8.1	8.9	7.7
Brinell Hardness	340	340	340	...	...	...
Izod Impact, ft-lb	31 to 32	20 to 20	20 to 20	8 to 9	10 to 12	12 to 13

One-half of the specimens were then tested in order to show the physical characteristics of the steel at this stage, and it is assumed these characteristics would be retained in the core of the nitrided specimens.

The other specimens were nitrided by the Ludlum Steel Co., being given a 90-hour treatment at 950° F.

A number of the un-nitrided fatigue specimens remained after the tests in that condition, and these were nitrided in the Westinghouse laboratory, and additional fatigue tests were made. The nitriding was carried out at 1000° F. for 48 hours.

The fatigue tests were made in the testing machines illustrated in Fig. 3, seven machines of this type being available and used in the investigation. They operate at a speed of 1750 r.p.m.

The impact tests were made in a 120-ft-lb. Izod machine. The hardness of the nitrided surface was determined with a Vickers Pyramid hardness testing machine.

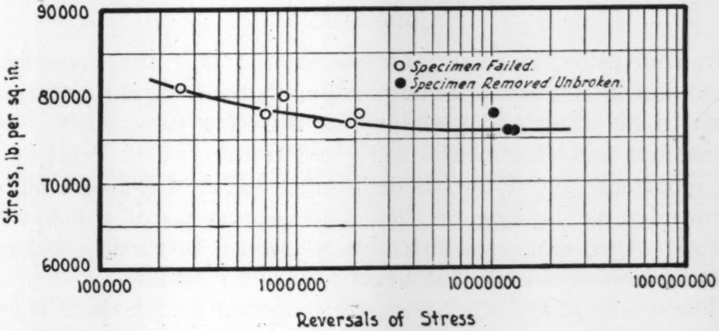

FIG. 4.—Results of Fatigue Tests on Chromium-Aluminum-Molybdenum Steel Before Nitriding.

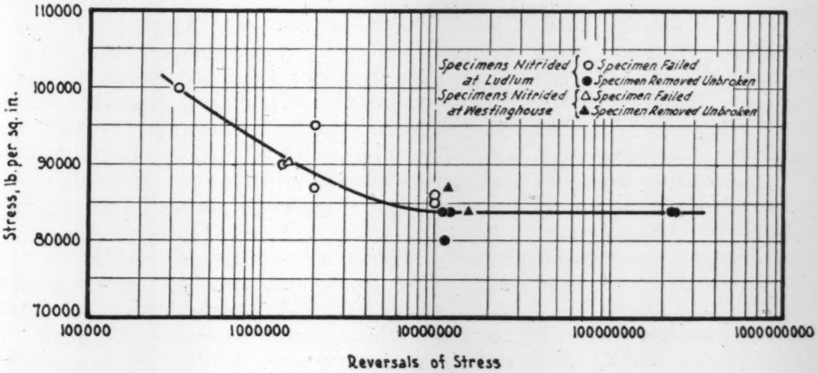

FIG. 5.—Results of Fatigue Tests on Chromium-Aluminum-Molybdenum Steel After Nitriding.

TEST DATA

The results of the tension, impact and hardness tests are given in Table I.

The nitrided specimens exhibited a hardness of 974 to 1064, Vickers Pyramid number.

The results of the fatigue tests of the heat-treated specimens before nitriding are shown graphically in Fig. 4, and the results after nitriding in Fig. 5. The endurance limit before nitriding is placed at 76,000 lb. per sq. in., and after nitriding at 84,000 lb. per sq. in. Two specimens were tested at 84,000 lb. per sq. in. to 225,000,000 reversals without failure.

CONCLUSION

In conclusion, it should be emphasized that the investigation covered but one lot and one composition of steel, but one preparatory process to nitriding and perhaps two nitriding treatments. Other compositions and treatments may yield results not in keeping with those reported. No doubt the endurance value of the core material has considerable bearing on the endurance value of the hardened material. Also, any marked tendency towards brittleness and spalling of the case would result in lower endurance values.

The results of the other tests are comparable with those reported elsewhere for like materials and treatments.

Acknowledgment.—The author acknowledges the valuable assistance of Mr. E. A. Snader in this work.

THE INFLUENCE OF STRESS RANGE AND CYCLE FREQUENCY ON CORROSION[1]

By D. J. McAdam, Jr.[2]

Synopsis

Part I of this paper gives a brief résumé of previous work, an outline of continued investigation and a description of methods and material.

Part II discusses the influence of cyclic stress on corrosion as illustrated by Type 5 diagrams. Stressless corrosion, total damage and net damage are illustrated. Methods are given for deriving other diagrams to illustrate the influence of stress range and cycle frequency on corrosion.

Parts III, IV and V discuss influence of stress range and cycle frequency on corrosion of steels, aluminum alloys and monel metal. The field of investigation has been extended to include the influence of nominal stresses far above the endurance limit and even above the tensile strength. Influence of cycle frequency is illustrated by constant net-damage diagrams, Type 10. Influence of stress range is illustrated by constant net-damage diagrams, Type 11 (*a*). Forms of Type 10 diagrams for different alloys are compared and classified. Type 11 (*a*) graphs for steels are nearly straight, nearly parallel lines. For duralumin and monel metal, Type 11 (*a*) graphs representing frequencies of about 50 cycles per minute or less are nearly straight and nearly parallel; graphs representing higher frequencies are not straight and parallel.

Part VI discusses the influence of stress range and cycle frequency on the rate of net damage. Total damage may proceed at a continually increasing rate. Or it may proceed first at a decreasing, then at an increasing rate. Net damage, for all metals, however, probably proceeds at a continually increasing rate. Relationship between corrosion stress and the initial rate of net damage is a logarithmic straight-line relationship. The initial rate of net damage varies as a power of the corrosion stress. The power exponent varies with the metal, and probably with the corrosion conditions.

Part VII is a general discussion of the influence of cyclic stress on corrosion. Influence of cyclic stress on the surface film and on the metal itself are discussed with reference to the forms of the Type 10 graphs for various alloys.

PART I—OUTLINE OF INVESTIGATION, DESCRIPTION OF METHODS AND MATERIAL

Previous Investigation of Influence of Cyclic Stress on Corrosion

The effects of simultaneous corrosion and cyclic stress of relatively high frequency were investigated at the U. S. Naval Engi-

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[1] Published by permission of the Secretary of the Navy, U. S. A.

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neering Experiment Station, and the results were presented in five papers(**1-5**).[1] The entire process that results in failure of metals under these conditions was called "corrosion-fatigue." In these papers references were given to a paper on this subject by Haigh in 1917(**6**).

In the fourth paper(**4**) it was shown that if the initial stress is below the endurance limit, the corrosion-fatigue process can be divided into two periods. The first period is the formation of corrosion pits. The pitting, however, is not the ordinary pitting of stressless corrosion, but is an accelerated pitting due to the influence of the cyclic stress on the corrosion. Pits formed under simultaneous corrosion and cyclic stress are sharper and deeper than pits formed in the same time under stressless corrosion.

As pitting progresses, the actual stress at the bottoms of the corrosion pits increases owing to stress concentration. When the increasing actual stress surpasses the endurance limit, the second period of corrosion-fatigue begins. In this period the metal is subjected to ordinary fatigue as well as to the accelerated corrosion pitting. If the process continues, the metal finally fails by fatigue. If the cycle frequency is low, however (as in many metals in service), corrosion pitting may end the usefulness of the metal before it has been subjected to a sufficient number of cycles to be affected by ordinary fatigue.

An understanding of the influence of cyclic stress on corrosion, therefore, is not only necessary to an understanding of failures due to corrosion-fatigue, but has a much wider application to the behavior of metals in service. As practically no quantitative information on this subject was available, an investigation was begun at the Naval Engineering Experiment Station. Results of this investigation have been presented in five papers(**7-11**).

These five papers discussed the effect of cyclic stress on corrosion of a number of ferrous and non-ferrous metals. The damaging influence of corrosion was estimated by determining the resultant lowering of the fatigue limit.

OUTLINE OF CONTINUED INVESTIGATION OF THE INFLUENCE OF CYCLIC STRESS ON CORROSION

Object and Methods.—The object of the investigation described in the present paper was to study further the effect of the three variables, stress, time and number of cycles, on the resultant fatigue limit. The interrelationship between four variables, therefore, is to be considered.

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[1] The boldface numbers in parentheses refer to the papers given in the list of references appended hereto.

The method of experiment was that described in the five previous papers(7-11). Each experiment consisted of two stages. In the first or corrosion stage, the specimen was subjected to cyclic stress while in contact with water. In the second or fatigue stage, the corroded specimen, after being oiled, was subjected to a fatigue test at 1450 r.p.m. in air.

The term "corrosion stress" will be used to designate the cyclic stress applied in the first or corrosion stage. The term "fatigue limit" or "resultant fatigue limit" will be used to designate the fatigue limit obtained in the second stage.

Relationships between corrosion stress, time, number of cycles, and resultant fatigue limit are represented by diagrams of various types. Other diagrams have been developed to illustrate the influence of stress range or cycle frequency on the rate of net damage.

Extension of the Field of Investigation.—In the investigation described in the previous papers(7-11) it was assumed that attention should be confined to the first period of corrosion-fatigue. It appeared probable that in the second period of corrosion-fatigue the progress of pitting would be due not only to corrosion, but also to ordinary fatigue. For this reason initial corrosion stresses used in the previous investigation were below the endurance limit and attention was given entirely to the first period of corrosion-fatigue.

It has now been found, however, that throughout a large part of the second period of corrosion-fatigue the progress of pitting is practically uninfluenced by ordinary fatigue, but is due entirely to corrosion differing only in degree from stressless corrosion. Discovery of this fact has made it possible to extend the field of investigation to include the effects of initial nominal stresses far above the endurance limit, even above the tensile strength of the metal. This extension has given much additional information about the forms of the derived graphs, especially the graphs representing low cycle frequency.

Fatigue Corrosion.—The name "corrosion-fatigue" was given to the entire process, starting with corrosion accelerated by cyclic stress and ending with failure by fatigue. It now seems desirable that a name be given to the corrosion pitting that proceeds throughout the first period and a large part of the second period of corrosion-fatigue. For this corrosion process, differing only in degree from stressless corrosion, the name "corrosion-fatigue" is not suitable. The name "fatigue corrosion" is more suitable. As the process is corrosion accelerated by cyclic stress it may be called "fatigue corrosion," with the understanding that the name does not imply that the process is similar to ordinary fatigue. This name will be used in the present paper.

TABLE I.—CHEMICAL COMPOSITION OF MATERIAL.

All values are averages of at least two determinations, usually more.

Material	Designation	Carbon, per cent	Manganese, per cent	Phosphorus, per cent	Sulfur, per cent	Silicon, per cent	Nickel, per cent	Chromium, per cent	Copper, per cent	Iron, per cent	Magnesium, per cent	Aluminum, per cent
Nickel Steel	IW	0.28	0.50	0.015	0.036	0.19	3.70	0.26	....	....	....	.....
Chromium-Nickel Steel	AX	0.36	0.48	0.013	0.015	0.22	3.26	1.55	....	....	....	.....
Chromium-Nickel Steel	BC	0.28	0.69	0.014	0.016	0.21	1.51	0.73	....	....	....	.....
Monel Metal, cold rolled	EP	0.16	0.95	0.015	0.017	0.05	67.51	....	29.54	1.76	....	.....
Duralumin, tempered	KI	....	0.72	.....	.....	0.36	.....	....	4.37	0.69	0.55	93.31[a]
Duralumin, tempered	LG	....	0.58	.....	.....	0.40	.....	....	4.04	0.68	0.35	93.95[a]
Aluminum-Manganese Alloy	JS	....	1.35	.....	.....	0.16	.....	....	0.15	0.59	....	97.76[a]

[a] By difference.

TABLE II.—HEAT TREATMENTS OF MATERIAL.

Material	Designation	Temperature Heated, deg. Fahr.	Time Held, minutes	Cooled in	Temperature Reheated, deg. Fahr.	Time Held, minutes	Cooled in
Nickel Steel	IW-W-10	1450[a]	60	Water	1000	120	Furnace
Chromium-Nickel Steel	AX-W-10	1550	60	Water	1000	120	Furnace
Chromium-Nickel Steel	BC-W-10	1550	60	Water	1000	120	Furnace
Monel Metal, cold rolled	EP-8	800	180	Furnace			
Duralumin, tempered	KI	As Received[b]					
Duralumin, tempered	LG	As Received[b]					
Aluminum-Manganese Alloy	JS	As Received					

[a] Previously heated to 1675° F., held 60 minutes, cooled in air.
[b] Heat treated by manufacturer.

TABLE III.—RESULTS OF TENSION, CHARPY AND ENDURANCE TESTS.

Unless otherwise indicated, each value is the result of two determinations, except endurance values.

Material	Condition	Designation	Tensile Strength, lb. per sq. in.	Johnson Limit, lb. per sq. in.	Proof Stress, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Charpy Impact Value, ft-lb.	Endurance Limit, Rotating Cantilever, lb. per sq. in.
Nickel Steel	Quenched and Drawn	IW-W-10	128 100[a] ±2 800	114 000[a] ±3 000	114 600[a] ±3 000	110 000[a] ±2 600	94 300[a] ±2 600	20.6[a] ±0.8	61.8[a] ±0.8	29.0 ±0.0	64 000
Chromium-Nickel Steel	Quenched and Drawn	AX-W-10	162 200[b] ±1 700	143 500[b] ±2 200	146 300[b] ±2 400	141 600[b] ±3 450	104 000[b] ±3 200	16.2[b] ±0.5	50.6[b] ±0.5	8.5 ±0.4	89 500
Chromium-Nickel Steel	Quenched and Drawn	BC-W-10	137 700[c] ±2 500	120 800[c] ±3 600	122 600[c] ±3 600	117 100[c] ±3 200	101 900[c] ±4 800	19.4[c] ±0.8	58.3[c] ±1.1	30.6 ±3.0	68 000
Monel Metal, cold rolled	Annealed	EP-8	128 900[d] ±700	94 100[d] ±1 000	95 600[d] ±600	88 600[d] ±1 400	81 300[d] ±1 700	20.4[d] ±0.8	58.0[d] ±0.4	53.6 ±2.6	52 000
Duralumin, tempered	As Received	KI	61 350[e] ±2 750	30 700[e] ±2 100	31 250[e] ±2 150	29 300[e] ±2 300	28 900[e] ±2 400	24.8[e] ±1.3	38.3[e] ±1.3	7.0 ±0.3	......
Duralumin, tempered	As Received	LG	56 300[b] ±1 100	28 100[b] ±700	28 900[b] ±1 000	27 100[b] ±750	26 100[b] ±400	24.7[b] ±0.9	40.6[b] ±0.5	7.8 ±0.1	.....
Aluminum-Manganese Alloy	As Received	JS	29 000[b] ±350	17 600[b] ±600	16 800[b] ±225	11 200[b] ±450	10 500[b] ±750	10.0[b] ±0.25	36.2[b] ±1.3	5.1 ±0.4	10 700

[a] Twenty-three determinations.
[b] Four determinations.
[c] Eleven determinations.
[d] Nine determinations.
[e] Seventeen determinations.

Machines and Specimens.—The rotating cantilever machines and specimens used in most of the experiments have been described in previous papers(12, 13). The method of polishing has also been described(13, 14).

The machine for making rotating cantilever tests at 10,000 r.p.m. described in a previous paper(10), has been improved so that it now gives no more trouble than do the machines running at lower frequencies. Vibration of the specimen is prevented by suitable dampening of the applied load by a dash pot. Two machines are now in continuous use.

Corrosion Stage.—In the corrosion stage, the specimens were corroded in a water stream, which was diagonally applied so as to surround with water the tapered portion of the specimen. Specimens were thus corroded under various stresses and cycle frequencies, for various times and numbers of cycles. For comparison, other specimens were corroded without stress. The carbonate water used in these experiments has been described in previous papers(1, 2, 3, 4).

Material, Chemical Composition and Heat Treatment.—Material for this investigation was obtained in the form of round rods 1 in. in diameter. The chemical composition for the alloys used is given in Table I. Details of heat treatment are given in Table II.

Tension and Impact Tests.—Results of tension and Charpy impact tests are given in Table III. In this table, "elastic limit" means the highest stress that leaves no appreciable permanent deformation after removal of the load. "Proof stress" means the stress that results in a permanent deformation of 0.0001 in. per inch of length after removal of the load.

PART II—TOTAL DAMAGE AND NET DAMAGE AS ILLUSTRATED BY TYPE 5 DIAGRAMS

GENERAL DESCRIPTION OF TYPE 5 DIAGRAMS

Type 5 diagrams have been discussed in three previous papers(9, 10, 11). In these diagrams, abscissas represent corrosion times and ordinates represent fatigue limits of the previously corroded specimens.

Representative Type 5 diagrams are shown in Figs. 1 to 3, inclusive. Each graph in these figures represents the relationship between corrosion time and resultant fatigue limit, for a chosen stress and cycle frequency. Each series of graphs represents some one cycle frequency. Comparison of the graphs of any series, therefore, throws light on the effect of corrosion stress. Each experimental point represents the results obtained with a single specimen. The method of obtaining resultant fatigue limits by extrapolation of stress-cycle graphs has been illustrated and described in previous papers(7, 8). To save space, stress-cycle graphs have not been included in this paper.

All the graphs of a series have a common origin. The ordinate of this common origin represents the endurance limit of the metal (as obtained by test of uncorroded specimens). The course of each graph illustrates the decrease in resultant fatigue limit with increase in corrosion time. The uppermost graph of each series represents the effect of stressless corrosion. Every other graph represents the effect of fatigue corrosion under the indicated cyclic stress.

STRESSLESS-CORROSION GRAPHS

For ordinary steels and for aluminum alloys, the slope of the stressless-corrosion graph is at first steep. With increase in the corrosion time, however, the slope gradually decreases until the graph becomes practically horizontal. Graphs of this kind, therefore, were called "retarded-damage" graphs.

For corrosion-resisting steels and for monel metal, as shown in two previous papers(10, 11), the slope of the stressless-corrosion graph is at first very slight. The slope increases very little with increase in corrosion time to 100 or even to more than 200 days. With further increase in corrosion-time, the slope of the graph gradually increases, and probably becomes steep. Graphs of this kind, therefore, were called "accelerated-damage" graphs.

The stressless corrosion graphs for duralumin in Figs. 1 and 2 are composite graphs obtained with samples JU and KA, which were illustrated in a previous paper(11), and with a few specimens of sample LG. The physical properties of all these samples are practically the same.

INFLUENCE OF CYCLIC STRESS ON CORROSION, AS ILLUSTRATED BY TYPE 5 DIAGRAMS

In each group of Type 5 diagrams, as illustrated in Figs. 1 to 3, the graphs representing various corrosion stresses and the graph representing stressless corrosion all have a common origin. As they extend to the right, however, the graphs separate. The greater the corrosion stress, the steeper is the course of the graph.

For monel metal, as shown in Fig. 3 of the present paper and in two previous papers(10, 11), the Type 5 graphs representing fatigue corrosion (like the graph representing stressless corrosion) are accelerated-damage graphs.

For ordinary steels, as shown in Fig. 1 of the present paper and in three previous papers(9, 10, 11), the graphs representing fatigue corrosion (except possibly graphs representing high corrosion stresses) probably start as retarded-damage graphs. If continued far enough, however, the curvature is reversed and the graphs descend with increasing steepness to the axis of abscissas.

For aluminum alloys, as shown in Figs. 1 and 2 of the present paper and in a preceding paper(11), the Type 5 graphs representing fatigue corrosion vary greatly in curvature. The curvature of these graphs is greatly influenced by their proximity to the stressless-corrosion graph. For this reason, some of the graphs near their origin are similar in curvature to the stressless-corrosion graph. As they extend to the right, however, the curvature of these graphs is reversed and they turn downward. Other graphs, especially those representing the higher stresses, probably curve downward from the origin. It will be shown that the above described differences in curvature of the Type 5 graphs for various metals are due to the influence of stressless corrosion. For all metals, net damage probably proceeds at an increasing rate.

TOTAL DAMAGE AND NET DAMAGE

Total damage and net damage have been discussed in three previous papers(9, 10, 11). The total damage due to fatigue corrosion is measured by the distance of the Type 5 graph (at any point) below a horizontal line through the origin of the graph. This damage, however, is not due entirely to cyclic stress. The effect of the cyclic stress is measured by the vertical distance of the Type 5 graph (at any point) below the stressless-corrosion graph. The net damage, therefore, is the total damage less the damage that would be caused in the same time by stressless corrosion. The influence of cyclic stress is measured by net damage rather than by total damage.

By "constant net damage" is meant constant (percentage) lowering of the fatigue limit below the fatigue limit that would result in the same time from stressless corrosion. To represent constant net-damage, therefore, a line may be drawn in a Type 5 diagram so that its ordinates will be a constant percentage of the corresponding ordinates of the stressless-corrosion graph. The broken lines in Figs. 1 to 3 have been so drawn. The net damage represented by these lines is 15 per cent. The stresses and coordinates represented by the intersections of these lines with the Type 5 graphs may be used in deriving various graphs to represent the stress-time-cycle relationship for constant net-damage. Diagrams derived in this way are shown in Figs. 4 to 9, inclusive.

In deriving these constant net-damage diagrams, the Type 5 working diagrams were plotted on scales that were most suitable for the purpose. The scales used in these working diagrams were not necessarily the same as the scales used in Figs. 1 to 3. The graphs shown in Figs. 1 to 3 are merely illustrative. Some graphs have been omitted.

PART III—THE INFLUENCE OF STRESS-RANGE AND CYCLE FREQUENCY ON CORROSION OF STEELS

Constant Net-Damage Diagrams

The influence of cyclic stress on corrosion is represented better by constant net-damage diagrams than by constant total-damage diagrams. Several types of constant net-damage diagrams may be derived from Type 5 diagrams. Two types, however, have proved most useful. These are Types 10 and 11(*a*), which were presented in three previous papers(9, 10, 11). Type 11(*a*) diagrams illustrate the influence of corrosion stress on net damage. Type 10 diagrams illustrate the influence of total number of cycles and of cycle frequency on net damage.

For ordinary steels, the relationship between corrosion stress and the time necessary to cause constant net damage (at constant cycle frequency) may be represented on a logarithmic scale by practically straight sloping lines. This was shown by the Type 11(*a*) diagrams in three preceeding papers(9, 10, 11). Before presenting additional evidence, however, about the form of the Type 11(*a*) graph for steels and for other alloys, it seems desirable to discuss the influence of cycle frequency on net damage.

In discussing the Type 10, Type 11(*a*) and other diagrams, the direction of the axis of abscissas will be viewed as horizontal and the direction of the axis of ordinates will be viewed as vertical. It should be noted that this use of the words "horizontal" and "vertical" is not appropriate when a Type 10 diagram is studied as the plan or top view of a three-dimensional diagram. When a Type 10 diagram is viewed thus, both coordinates should be considered as horizontal, and the stress coordinate (perpendicular to the plane of the Type 10 diagram) should be viewed as vertical. In the present paper, however, Type 10 and Type 11(*a*) diagrams will be discussed as two-dimensional diagrams.

The Influence of Cycle Frequency on Net Damage

A Type 10 graph is a constant-stress graph representing the relationship between total number of cycles and the time necessary to cause constant net damage. A Type 10 graph also represents the relationship between cycle frequency and the time necessary to cause constant net damage. The time necessary to cause constant net damage, however, varies inversely as the average rate of net damage. A Type 10 diagram, therefore, throws some light on the influence of cycle frequency on the average rate of net damage (throughout a total of 15 per cent net damage).

In the Type 10 graphs for ordinary steels, presented in three previous papers(9, 10, 11), no attempt was made to draw interpretative lines. Experimental points representing the same corrosion stress were merely connected by straight lines. Additional experiments have now been made with some of the same steels, so as to obtain additional points on the Type 10 diagrams, especially points representing experiments at 10,000 r.p.m. More complete Type 10 diagrams, therefore, can now be made, and it is now possible to draw interpretative lines to represent the forms of the ideal Type 10 graphs.

In Fig. 4 are shown two of these Type 10 diagrams for steels. In drawing the interpretative graphs in this figure, consideration has been given to each series as a whole. Each graph has been drawn to represent the most probable relationship to neighboring graphs.

The ideal Type 10 graphs for these two steels, over a range of frequency from 0.5 or less to 500 or 1450 r.p.m., are evidently nearly straight, nearly horizontal lines. This fact agrees with the tentative conclusions stated in previous papers(9, 10, 11). Within this range of frequency, however, as the graphs extend to the left, there is slight upward curvature. To the left of the diagonal line representing 1450 r.p.m. the upward curvature rapidly increases. At 10,000 r.p.m., the graphs representing low corrosion stresses become nearly vertical. The graphs representing higher corrosion stresses would evidently become nearly vertical, if extended to sufficiently high frequency. The higher the corrosion stress, the higher is the frequency at which the corresponding graphs would become practically vertical.

At cycle frequencies ranging from very low frequency to 1000 or 1500 per minute, therefore, net damage of steels depends chiefly on total number of cycles and depends very little on corrosion time. With increase of cycle frequency, net damage depends continually less on number of cycles, and continually more on total corrosion time. At very high frequencies, net damage (at constant corrosion stress) evidently depends chiefly on corrosion time and depends very little on number of cycles.

The average rate of net damage (throughout a total of 15 per cent net damage), for cycle frequencies ranging from very low frequency to 1000 or 1500 per minute, is nearly proportional to the cycle frequency. With increase in frequency, the average rate of net damage is continually less affected by change of frequency. At very high frequencies, the rate of net damage is nearly independent of cycle frequency.

In Fig. 5 is shown a Type 10 diagram for a new sample of chromium-nickel steel having high tensile strength. This high-strength material was used for the purpose of extending the field of investigation to stresses far above the endurance limit. Some of the graphs, as shown in the figure, represent corrosion stresses as high as 130,000, and a small portion of a graph represents a nominal stress of 200,000 lb. per sq. in. The range of corrosion stresses represented in this figure is several times as great as the range represented in any previous diagram of this type.

These graphs in Fig. 5 are similar in form and direction to the graphs in Fig. 4. Throughout a range of frequency from 0.5 or less to 1000 or 1500 cycles per minute the graphs are only slightly curved and are nearly horizontal. If extended far enough to the left the graphs would evidently become practically vertical. If extended far enough to the right, the curvature may be reversed and the graphs may curve downward. This has not yet been determined.

In a preceding paper(11), Type 10 graphs for stainless iron and steel were presented and discussed. In spite of the wide scatter of results, it is evident that these graphs are nearly horizontal, at least within a range of frequency from 0.5 to 1500 cycles per minute. Type 10 graphs for all steels, therefore, are probably similar in direction and form.

THE INFLUENCE OF CORROSION STRESS ON NET DAMAGE

For steels, as shown in three previous papers(9, 10, 11), the relationship between corrosion stress and the time necessary to cause constant net damage can be represented on a logarithmic scale by practically straight lines. This relationship is illustrated in these papers by Type 11(*a*) diagrams. In the present paper are shown additional Type 11(*a*) diagrams based on more complete data, including results of tests at corrosion stresses far above the endurance limit.

In Fig. 8 are shown Type 11(*a*) diagrams for the same nickel steel that is represented by a Type 10 diagram in Fig. 4, and for the same chromium-nickel steel that is represented by a Type 10 diagram in Fig. 5. Abscissas in Type 11(*a*) diagrams are measured from right to left. This unusual arrangement is made so that each diagram with the corresponding Type 10 diagram will represent two views of a three-dimensional stress-time-cycle diagram.

The diagram in the upper part of Fig. 8, like the Type 10 diagram in Fig. 4, covers a wide range of corrosion stresses and cycle frequencies. In the diagram in the lower part of Fig. 8, the graphs have been extended to ordinates representing nominal corrosion stresses far above the endurance limit, even above the tensile strength. The range of stresses represented by these graphs is several times as great as the range represented by any previous graphs of this type.

The Type 11(*a*) graphs for steels are evidently nearly straight, nearly parallel lines. The graphs in the lower series, as they extend upward, show no tendency to bend to the right. The upper parts of these graphs, therefore, show no influence of ordinary fatigue. This is due to the fact that cyclic stress above the endurance limit causes no damage (as measured by lowering of the fatigue limit of a specimen) until the specimen is nearly ready to fail. The net damage represented in each graph in this diagram, therefore, is due entirely to corrosion pitting under the influence of cyclic stress.

For ordinary steels, therefore, as shown in this and previous papers(9, 10, 11), the relationship between corrosion stress and the time necessary to cause constant net damage is a logarithmic straight-line relationship. The straight line relationship covers a range of corrosion stresses from 2000 or less to probably 200,000 lb. per sq. in.

PART IV—THE INFLUENCE OF STRESS RANGE AND CYCLE FREQUENCY ON CORROSION OF ALUMINUM ALLOYS

Previous Investigation of the Influence of Cyclic Stress on Corrosion of Aluminum Alloys

Fatigue corrosion of the aluminum-manganese alloy, commercially known as 3SH, was discussed in a preceeding paper(11). The Type 10 graphs for this alloy were found to be decidedly curved. The curvature obtained was greater than in any Type 10 graphs obtained previously.

Type 10 graphs for duralumin were presented in two previous papers(10, 11). At that time, however, the experimental points, on which the graphs were based, were few and the scatter was relatively great. No interpretative graphs, therefore, were presented in these papers. The experimental points of each series were merely connected by short, straight lines. The evidence at that time seemed to indicate that the ideal graphs would be straight or only slightly curved lines. The discovery of the pronounced curvature of the Type 10 graphs for the aluminum-manganese alloy(11), however, suggested the possibility that the ideal graphs for duralumin also are curved. It seemed desirable, therefore, to investigate further the form of the Type 10 graph for duralumin.

The Influence of Cycle Frequency on Corrosion of Duralumin

On account of the double curvature of the Type 5 graphs for duralumin and the scatter of experimental points, a relatively large number of experiments were necessary to determine each Type 5 series and thus make it possible to establish the form of the derived Type 10 graphs. The Type 10 diagrams in Fig. 6, representing two samples of duralumin, have been derived from thoroughly established Type 5 series. It is now possible, therefore, to draw interpretative graphs for duralumin.

As shown by the interpretative lines in Fig. 6, the Type 10 graphs for duralumin are decidedly curved. The curvature is most abrupt at the constant-frequency line representing 10 r.p.m. Between 1.5 and 10 r.p.m., the graphs are nearly horizontal. With increase in frequency above 10 r.p.m., the graphs curve abruptly upward. With increase in frequency above 50 r.p.m., the graphs representing low corrosion stresses become practically vertical. The graphs representing higher corrosion stresses would evidently become practically vertical if extended to sufficiently high frequencies. The higher the corrosion stress, the higher is the frequency at which the graph would become vertical.

In obtaining the Type 10 graphs for duralumin presented in previous papers(10, 11), no experiments were made at 10 r.p.m. The absence of experimental parts representing 10 r.p.m., and the small number of experimental points representing 1.5 r.p.m., made it impossible at that time to detect the abrupt curvature of the Type 10 graphs for duralumin.

The Type 10 diagram for duralumin is qualitatively similar to the Type 10 diagrams for steels shown in Figs. 4 and 5. The diagram for duralumin differs from the diagram for steels, chiefly in the cycle frequency at which the graphs begin to curve abruptly upward. For steels this frequency is 500 to 1500. For duralumin the frequency is about 10 r.p.m. For steels and for duralumin, the graphs at low frequencies are nearly horizontal.

It should be noted, however, that the diagrams for the two samples of duralumin represented in Fig. 6 differ considerably in position. The graphs for sample LG are further to the right than the corresponding graphs for sample KI. As these two samples differ only slightly in physical properties, the greater resistance of sample LG to fatigue corrosion must be due to other causes. It is worthy of note that samples of duralumin differ greatly in their behavior when subjected to ordinary fatigue. This subject was discussed by the author in commenting on a paper by Johnson and Oberg(18).

For duralumin as for steels, the field of investigation has been extended to include corrosion stresses far above the endurance limit. As shown in Fig. 6 the graphs representing these high corrosion stresses, as they extend to the left, first curve upward, then the curvature is reversed. This reversal of curvature at high frequency may be due to the influence of rise of temperature in the specimens.

The Type 10 graphs for the aluminum-manganese alloy presented in a previous paper(11) resemble the graphs for duralumin in form and in the cycle frequency at which the graphs begin to curve abruptly upward. The Type 10 graphs for the aluminum-manganese alloy have not been accurately determined for frequencies below 10 r.p.m. There is some evidence, however, that the graphs as they extend to the right reverse their curvature at very low frequency and curve downward. Additional evidence on this point is needed.

THE INFLUENCE OF STRESS RANGE ON CORROSION OF DURALUMIN

In Fig. 9 are shown Type 11(*a*) diagrams for the same two samples of duralumin that are represented in Fig. 6. The graphs have been extended to stresses far above the endurance limit. This extension has made it possible to determine more definitely the form of the graphs, especially the graphs representing low cycle frequency.

The graphs representing cycle frequencies of 50 r.p.m. or less are evidently nearly straight and probably nearly parallel. As they extend upward, these graphs do not bend to the right as they would if there were much damage due to ordinary fatigue. The lower parts of graphs representing cycle frequencies of 10,000, 1450 and 500 r.p.m. are evidently nearly parallel to the 50 r.p.m. graph. As they extend upward, these three high-frequency graphs curve abruptly to the right at an ordinate representing stress of about 7000 lb. per sq. in. With further extension these three graphs then become nearly straight and slightly diverging.

Each of the Type 11(*a*) diagrams together with the corresponding Type 10 diagram should be considered as two views of a three-dimensional diagram.

PART V—THE INFLUENCE OF STRESS RANGE AND CYCLE FREQUENCY ON CORROSION OF MONEL METAL

PREVIOUS INVESTIGATION OF THE INFLUENCE OF CYCLIC STRESS ON CORROSION OF MONEL METAL

Fatigue corrosion of monel metal was discussed in two previous papers(10, 11). On account of the scatter of experimental points, however, interpretative Type 10 graphs were not drawn. The experimental points of each Type 10 series were merely connected by short, straight lines. The evidence at that time seemed to indicate that the ideal graphs, within the range of frequencies investigated, would be nearly straight lines converging toward the right, and making a much greater angle with the axis of abscissas than do the graphs for steels and aluminum alloys. Within the range of frequencies investigated, these graphs for monel metal showed no tendency to curve so as to become nearly horizontal.

THE INFLUENCE OF CYCLE FREQUENCY ON CORROSION OF MONEL METAL

To determine whether or not the Type 10 graphs for monel metal are similar in form to the Type 10 graphs for steels and for duralumin it is necessary to extend the diagram far into the region representing low cycle frequency. This task seemed almost hopeless, because of the very long corrosion times required, until it was found possible to use corrosion stresses far above the endurance limit. Use of these high corrosion stresses, however, has now made it possible to draw interpretative graphs and to extend them to low cycle frequencies.

A Type 10 diagram for monel metal is shown in Fig. 7. The monel metal is the same sample that was used in the investigation described in two previous papers(10, 11).

The graphs for monel metal differ considerably in form from the graphs for steels and for duralumin. The chief difference, however, is at the low-frequency end of the diagram. At the high-frequency end, the graphs for monel metal probably curve upward, as do the graphs for steels and aluminum alloys. As they extend to the right, however, the graphs for monel metal do not become nearly horizontal, but reverse their curvature and curve downward. If extended far enough to the right, the graphs would probably become practically vertical.

The nearly vertical part of these graphs would evidently represent the influence of steady stress. These graphs, therefore, give some idea of the relative influence of steady stress and cyclic stress on corrosion of monel metal. It is possible that the Type 10 graphs for steels and duralumin, if they were extended to sufficiently low frequency, would curve downward and become vertical. If so, these graphs would differ only qualitatively from the graphs for monel metal.

The graphs in Fig. 7 representing corrosion stresses greater than the endurance limit do not reverse their curvature as they extend to the left. If extended far enough to the left, these graphs evidently curve downward. The greatly accelerated damage represented by the high-frequency ends of these graphs is probably due to the influence of rise of temperature in the specimens. The low thermal conductivity of monel metal, as shown in a previous paper(1), makes this alloy very sensitive to the thermal effects of high cycle frequency.

The Influence of Stress Range on Corrosion of Monel Metal

A Type 11(*a*) diagram for monel metal, shown in Fig. 9, illustrates the influence of corrosion stress on the time necessary to cause 15 per cent net damage. Use of high corrosion stresses has made it possible to determine the forms and directions of the graphs, especially the graphs representing low cycle frequencies. This diagram and the Type 10 diagram shown in Fig. 9 should be studied as two views of a three-dimensional diagram.

Comparison of the diagram for monel metal in Fig. 9 with the diagrams for duralumin in the same figure shows that these diagrams are qualitatively similar. Graphs representing cycle frequencies of 50 r.p.m. or less are probably nearly straight and not far from parallel. Graphs representing high frequency, as they extend upward, curve to the right. For monel metal, the curvature is more pronounced than for duralumin. This is probably due, in part at least, to the much lower thermal conductivity of monel metal.

PART VI—THE RATE OF NET DAMAGE

Rates of Total Damage and Net Damage

The slope of a Type 5 graph at any point represents the rate of total damage. As illustrated by the Type 5 graphs in Fig. 3, the rate of total damage under fatigue corrosion may continually increase. Or, as illustrated by the graphs in Figs. 1 and 2, the rate may first decrease and then increase. The rate of total damage is evidently influenced by the rate of damage due to stressless corrosion. The rate of net damage is the rate of total damage minus the rate of damage due to stressless corrosion. The rate of net damage, rather than the rate of total damage, is a measure of the influence of cyclic stress on corrosion.

Relationship Between Net Damage and Corrosion Time

Rates of net damage cannot be determined directly from Type 5 diagrams. In order to investigate rates of net damage it is necessary first to obtain graphs showing the relationship between net damage and corrosion time. Graphs of this type, which has been called Type 14, are shown in Figs. 10 and 11.

In these figures, abscissas represent corrosion time and ordinates represent net damage (in per cent). Each Type 14 graph is obtained from a Type 5 graph. The abscissas of the Type 14 graph correspond to the abscissas of the Type 5 graph. The ordinates of the Type 14 graph represent the corresponding distances of the Type 5 graph (expressed in percentages) below the stressless-corrosion graph. The Type 14 diagrams in Figs. 10 and 11 were not necessarily obtained from the Type 5 diagrams in Figs. 1 and 2, but from other Type 5 diagrams plotted on the most suitable scales.

In Fig. 10 are shown Type 14 diagrams for the nickel steel, IW-W-10, that has been represented by diagrams of other types in Figs. 1, 4 and 8. The Type 5 graphs from which these Type 14 graphs have been derived descend first with decreasing slope, then with increasing slope. The Type 14 graphs, however, as shown in Fig. 10, ascend without reversal of curvature. The curvature of these graphs indicates that net damage proceeds at a continually increasing rate.

Type 14 graphs for all ordinary steels are probably similar in form, at least near their origin. If extended upward far enough, however, some Type 14 graphs may reverse their curvature. Such reversal is due to the previously discussed(8) strengthening of the metal at the bottoms of corrosion pits.

In Fig. 11 are shown Type 14 diagrams for duralumin. The Type 5 graphs, from which these Type 14 graphs are derived, are of various forms as illustrated in Figs. 1 and 2. In some of them the slope first decreases, then increases. In others the slope probably increases throughout the entire length. As shown in Fig. 11, however, the slope of the derived graphs continually increases. For this alloy, as for ordinary steels, net damage proceeds at continually increasing rate.

Type 14 graphs for corrosion-resisting alloys, such as monel metal and stainless iron, are not shown in this paper. These graphs, however, would be of the same form as the Type 14 graphs for ordinary steels and for duralumin. This is evident from the fact that the Type 5 fatigue-corrosion graphs for corrosion-resisting alloys curve downward rapidly from their origin, whereas the stressless-corrosion graph curves downward at a much slower rate. The evidence seems to indicate, therefore, that for all metals net damage proceeds at a continually increasing rate.

THE INITIAL RATE OF NET DAMAGE

The diagrams shown in Figs. 4 to 9 represent the times necessary (under varying conditions of stress and cycle frequency) to cause 15 per cent net damage. Reciprocals of the time coordinates, therefore, represent average rates of net damage (throughout a total of 15 per cent net damage). The rate of net damage, as illustrated by Type 14 graphs in Figs. 10 and 11, continually increases. The nominal corrosion stress of each fatigue-corrosion experiment, moreover, is merely the initial corrosion stress. Only at the beginning of the fatigue corrosion, therefore, does the rate of net damage represent correctly the influence of the nominal corrosion stress. Knowledge of the relationship between the initial corrosion stress and the initial rate of net damage, consequently, would be of considerable interest.

The initial rate of net damage is measured by the slope of the tangent at the origin of a Type 14 graph. Tangents at the origins of some Type 14 graphs are represented in Figs. 10 and 11 by light lines.

For ordinary steels, the curvature of Type 14 graphs near the origin is probably rather slight. Hence by drawing the Type 14 graphs on suitable scales the tangents at the origin may be determined. For duralumin, as illustrated in Fig. 11, the curvature of Type 14 graphs near the origin is probably greater than for ordinary steels. By drawing each Type 14 graph on a suitable scale, however, the tangent at the origin can be determined with fair accuracy.

From the slopes of tangents at origins of Type 14 graphs, initial rates of net damage have been determined for various steels and aluminum alloys. These slopes have been determined from working graphs, not necessarily from the illustrative graphs shown in Figs. 10 and 11. Initial rates have been expressed as "per cent per day." These rates have been used in plotting graphs, designated Type 15, to represent the influence of corrosion stress on the initial rate of net damage.

INFLUENCE OF STRESS RANGE ON THE INITIAL RATE OF NET DAMAGE

Representative diagrams illustrating the influence of corrosion stress on the initial rate of net damage have been plotted with logarithmic coordinates in Fig. 12. For steels, the Type 15 graphs are nearly straight and nearly parallel.

For aluminum alloys, the graphs of each series as they extend upward remain nearly straight and nearly parallel until they reach the endurance limit. Above this point, the graphs representing low cycle frequencies remain nearly straight and nearly parallel, but the graphs representing high cycle frequencies curve to the right and diverge slightly. This curvature and divergence, which may be due to rise of temperature, is much less for the Type 15 graphs than for the Type 11(*a*) graphs shown in Fig. 9.

Type 11(*a*) diagrams are influenced by two factors, increasing stress concentration and accumulation of corrosion products. The former accelerates and the latter probably retards the rate of net damage. The influence of these two variables has probably been eliminated from the Type 15 graphs shown in Fig. 12. Possibly because of the elimination of these two variables, the Type 15 graphs for aluminum alloys are less curved and more nearly parallel than the Type 11(*a*) graphs.

Type 15 graphs for monel metal have not been obtained, as the slopes of the Type 5 diagrams for this alloy have not been determined with sufficient accuracy. It seems probable, however, that for all metals the relationship between corrosion stress and initial rate of net damage would be represented on a logarithmic scale by nearly straight lines, provided that the corrosion stress does not exceed the endurance limit.

The influence of stress range on corrosion, therefore, is probably represented more correctly by Type 15 than by Type 11(*a*) diagrams. The relationship between stress range and initial rate of net damage is evidently a logarithmic straight line relationship.

EQUATIONS REPRESENTING THE INFLUENCE OF CORROSION STRESS ON NET DAMAGE

The logarithmic straight line relationship between corrosion stress and the initial rate of net damage means that the initial rate of net damage varies as a power of the corrosion stress. The exponent of the power is the cotangent of the angle of slope of the Type 15 graph.

The relationship between corrosion stress and initial rate of net damage may be represented by the following equation:

$$R = CS^n$$

In this equation, R represents initial rate of net damage, S represents corrosion stress, and n represents the cotangent of the angle of slope of the Type 15 graph. C is a constant depending on the corrosion resistance of the metal, on the corrosion conditions, and on the cycle frequency. The following are approximate values for n:

For ordinary steels	3
For duralumin and aluminum-manganese alloy	4

It has not been possible to determine Type 15 graphs for monel metal. Comparison of the Type 15 graphs in Fig. 12 with the corresponding Type 11(*a*) graphs in Fig. 9, however, shows that the slopes of the Type 15 and Type 11(*a*) graphs for steels are nearly the same. For aluminum alloys, however, the slope of the Type 15 graphs is less than the slope of the Type 11(*a*) graphs. If the relationship between these two types of graph is the same for monel metal as for aluminum alloys, the value of n for monel metal is probably about 3.5.

It should be emphasized that these equations are applicable only when corrosion conditions are similar to those of the above described experiments.

PART VII—GENERAL DISCUSSION OF THE INFLUENCE OF STRESS RANGE AND CYCLE FREQUENCY ON CORROSION

INFLUENCE OF CYCLE FREQUENCY

The influence of cycle frequency is illustrated by the Type 10 diagrams in Figs. 4 to 7. These diagrams are of two classes. One class is represented by the diagrams for steels and aluminum alloys. The other class is represented by the diagram for monel metal. The graphs of the first class, as they extend to the left, become nearly vertical. As they extend to the right, they curve so as to become nearly horizontal. The graphs of the second class, as they extend to the left at high frequencies probably curve upward. As they extend to the right, however, the graphs of the second class do not become nearly horizontal, but reverse their curvature and curve downward. If extended far enough to the right, these graphs would probably become nearly vertical. Graphs of the first class also, if extended far enough to the right, may possibly reverse their curvature and become nearly vertical.

INFLUENCE OF STRESS RANGE AND CYCLE FREQUENCY ON THE SURFACE FILM

The influence of cyclic stress on net damage is evidently due largely to the cyclic deformation of the surface film and corrosion products. By "film" is here meant the entire primary layer that is affected by contact with the corrosive medium. That there is no distinct surface of demarcation between the film and underlying metal has been shown by the work of U. R. Evans(17) and others. The oxygen or other negative element penetrates to some extent the space lattice of the metal. The word "film" as here used applies not only to the oxide layer but also to the underlying layer of metal into which oxygen or other negative element has penetrated. By "corrosion products" is here meant the secondary compounds, such as rust, that are precipitated on the surface of the metal. The film and corrosion products together will be designated as the "coating."

Stressless corrosion involves diffusion of the negative ions inward and diffusion of the metal ions outward through the film. Corrodibility of a metal depends not only on the inherent solution pressure, but also largely on the permeability or "porosity" of the film. The resistance of stainless steel, for example, to fatigue corrosion as well as to stressless corrosion is greater than the resistance of ordinary steels because the surface film of stainless steel is less permeable than the film of ordinary steels. Investigation by Speller, McCorkle and Mumma(15, 16) has thrown much light on the influence of the surface film on corrosion-fatigue.

The evidence on the influence of stress and cycle frequency presented in the present paper suggests the following tentative ideas about the influence of cyclic stress on corrosion. These ideas are subject to change as additional evidence accumulates.

Stress increases the corrosion rate by increasing the permeability or effective "porosity" of the coating. If the applied stress remains steady, most of this increase in equivalent porosity is only temporary. There is temporarily increased diffusion of ions in both directions through the coating. This soon results in repair of the enlarged "pores," and the diffusion falls to the normal rate. If the stress is cyclic, however, there is in each cycle a temporary increase in porosity, resulting in temporarily increased rate of diffusion. The greater the stress range, the greater is this cyclic increase in porosity, and hence the greater is the rate of net damage.

INFLUENCE OF CYCLIC STRESS ON THE UNDERLYING METAL

Corrodibility of a metal, however, depends not only on the permeability of the coating, but also on the inherent solution pressure of the metal. Corrodibility of some metals, such as copper, is slight chiefly because of the low solution pressure. U. R. Evans(17) says that the surface film of copper is weakly protective. For many other metals also, corrosion resistance depends rather on low solution pressure than on the protective effect of the films.

The influence of cyclic stress on corrosion, therefore, may not be due entirely to cyclic distortion of the coating. The influence of cyclic stress, especially when the stress range is high, may be due partly to cyclic cold working of the metal. Cyclic cold working possibly increases the solution pressure. The effect on the solution pressure would probably be relatively greater for alloys of low inherent solution pressure than for alloys of high solution pressure.

THE FORM OF THE TYPE 10 GRAPH AS INFLUENCED BY PROPERTIES OF COATING AND UNDERLYING METAL

Type 10 diagrams of the first class all represent alloys having relatively high inherent solution pressure. Their resistance to corrosion depends chiefly on the protection afforded by the coating. The Type 10 diagram of the second class represents an alloy having relatively low inherent solution pressure. Additional information is needed to determine whether or not there is a general relationship between the form of the Type 10 graph and the solution pressure of the alloy. Further discussion of this subject, moreover, must be deferred on account of lack of space.

ACKNOWLEDGMENTS

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Acknowledgment is also due to the International Nickel Co. and the Aluminum Company of America for generous cooperation by supplying material.

NOTES TO FIGURES

In the diagrams, the phrase "at this point" means that the fatigue limit, estimated from a two-stage experiment, is as indicated in the diagram.

The phrases "above this point" and "beyond this point" mean either that the corrosion stage was not continued long enough or that the stress in the fatigue stage was not high enough to establish the exact position of the corresponding point in the diagram. It is known merely that the exact position is above or beyond the position indicated.

The arrow tips used in some of the diagrams indicate by their direction either that a specimen failed in the first stage of a two-stage experiment, or that, in order to reduce the resultant fatigue limit to the required value, the corrosion time must be greater than the value indicated by the position of the arrow tip.

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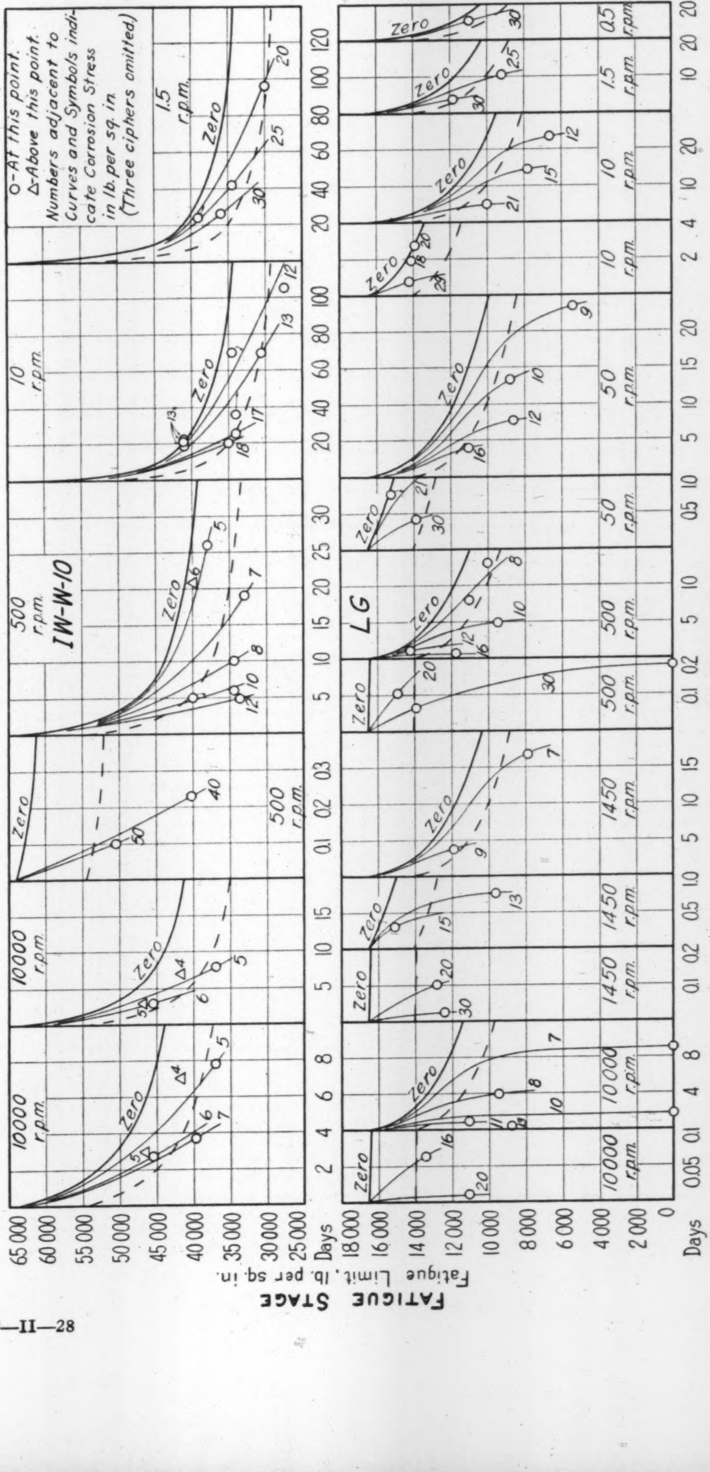

Fig. 1.—Type 5 Diagrams, Nickel Steel and Duralumin.

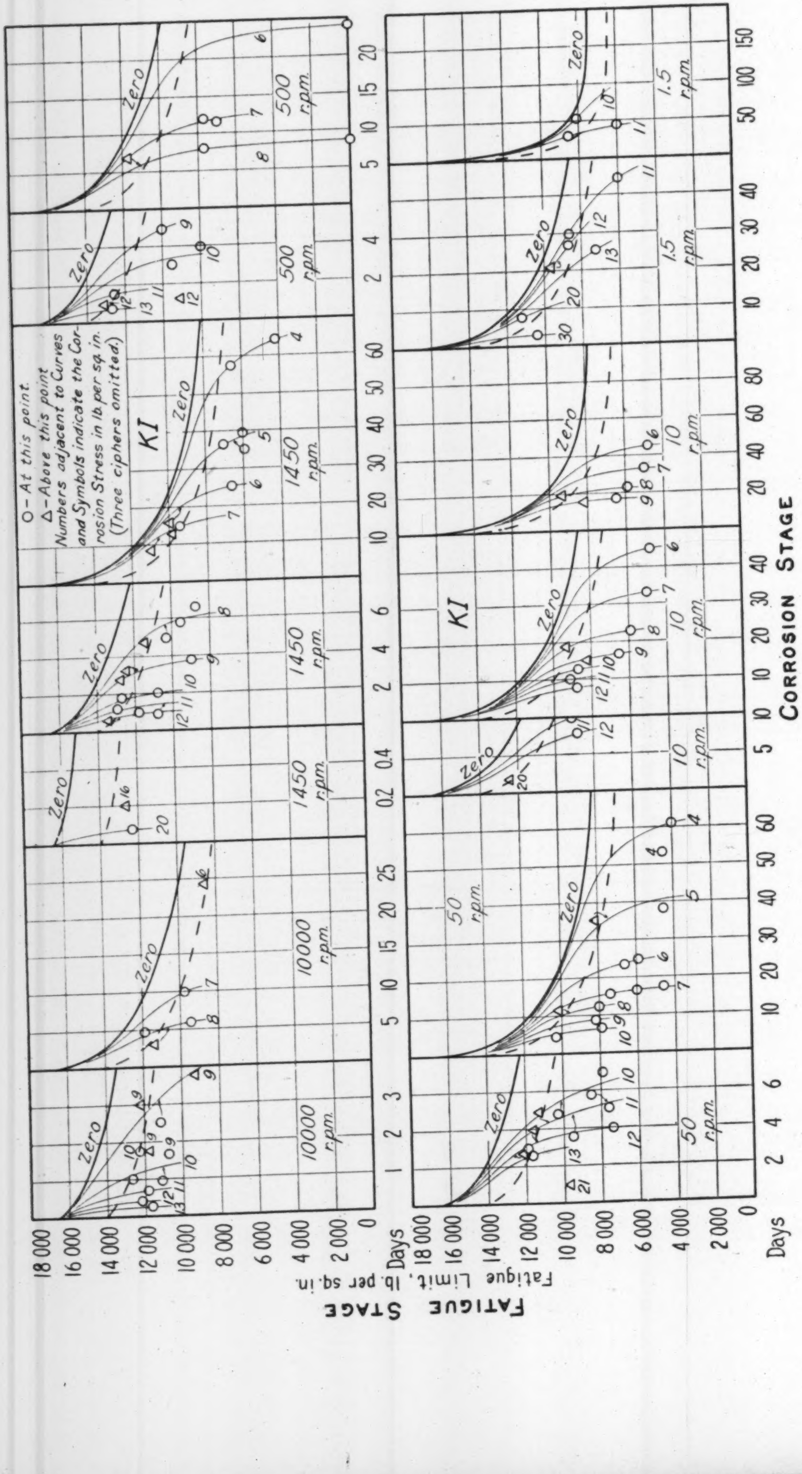

Fig. 2.—Type 5 Diagrams, Duralumin.

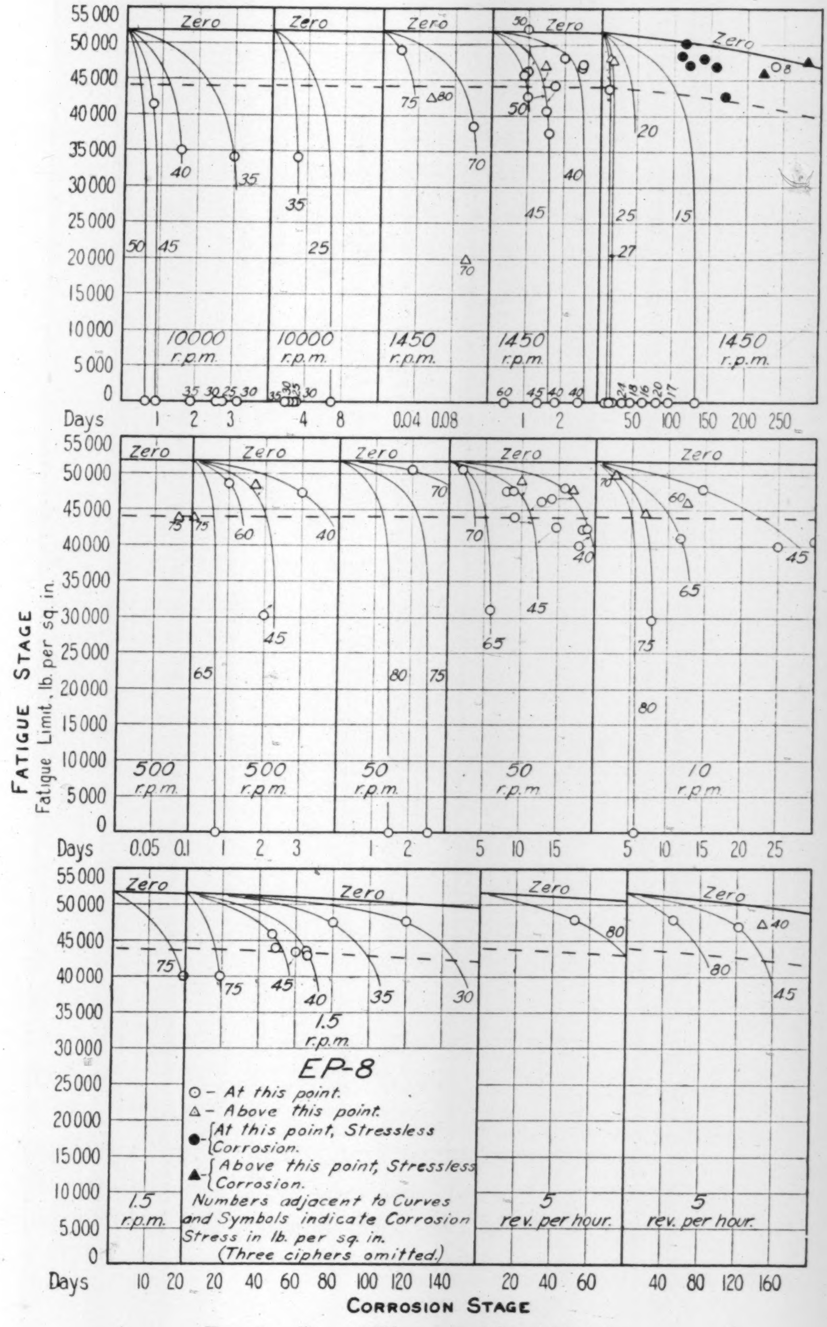

FIG. 3.—Type 5 Diagrams, Monel Metal.

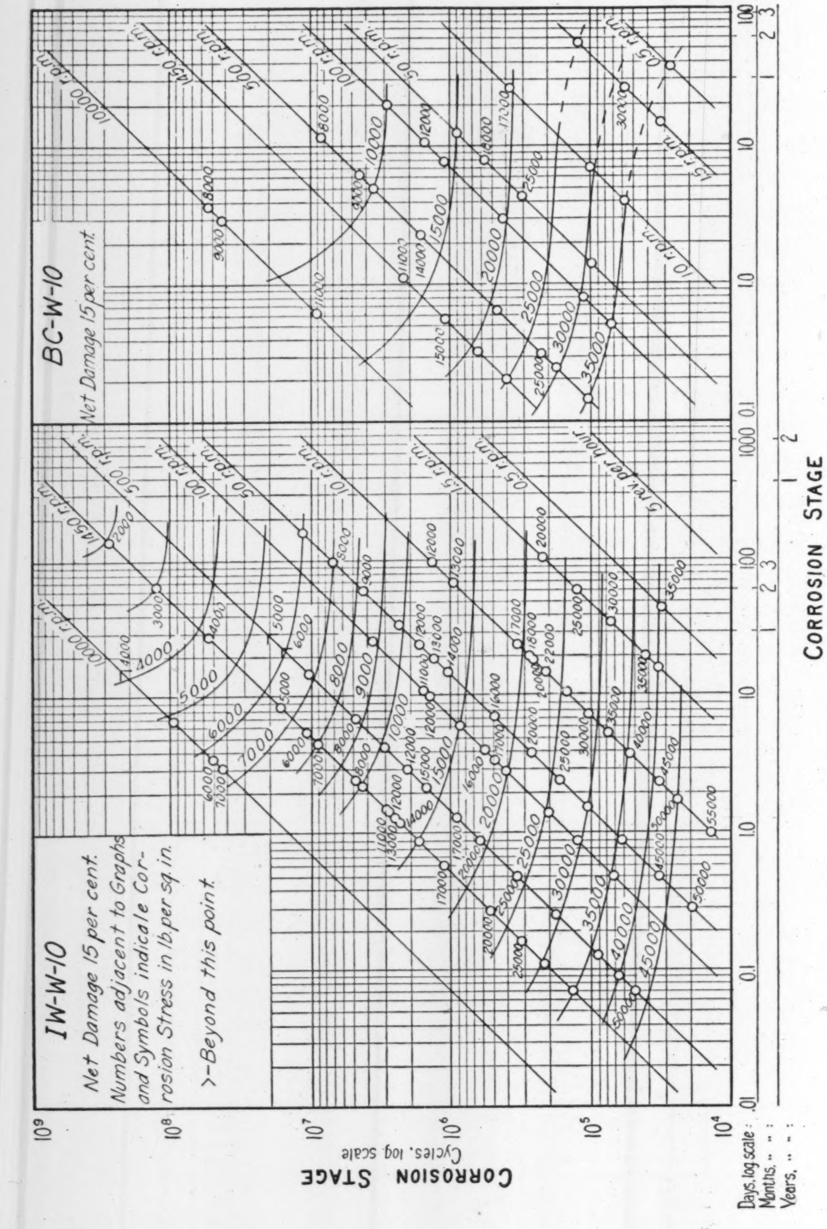

FIG. 4.—Type 10 Constant Net-Damage Diagrams, Nickel Steel and Chromium-Nickel Steel.

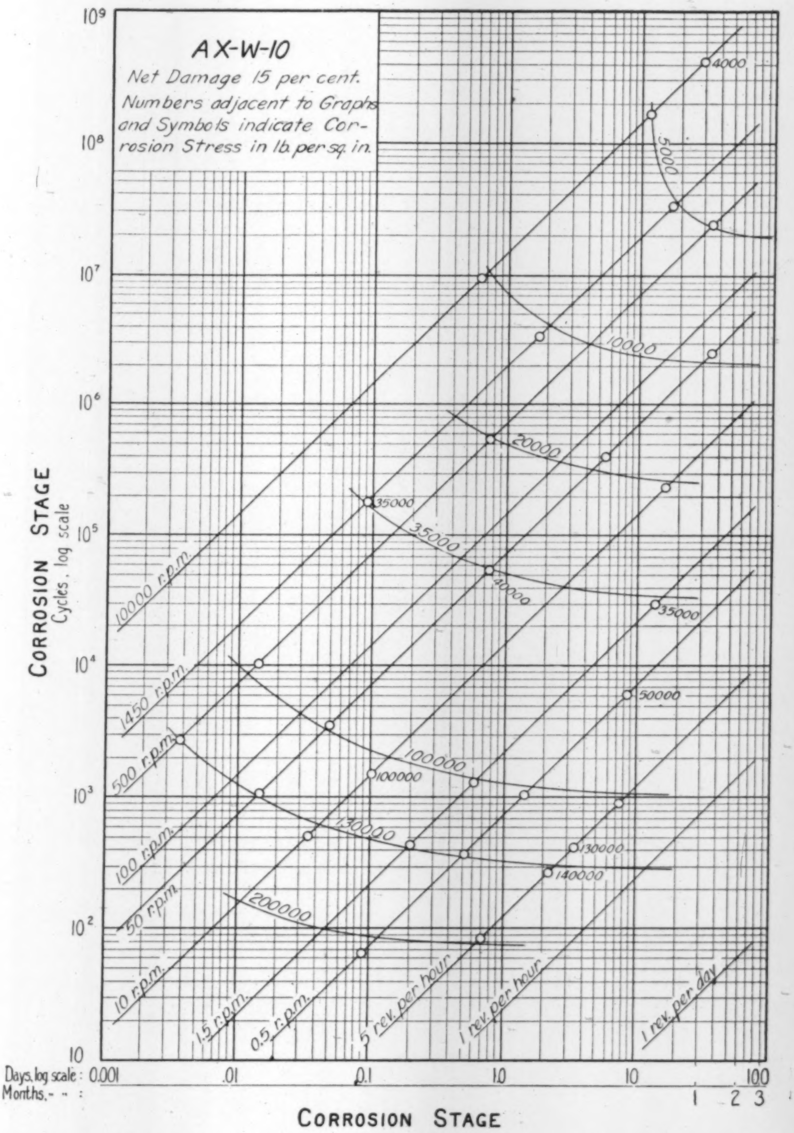

FIG. 5.—Type 10 Constant Net-Damage Diagram, Chromium-Nickel Steel.

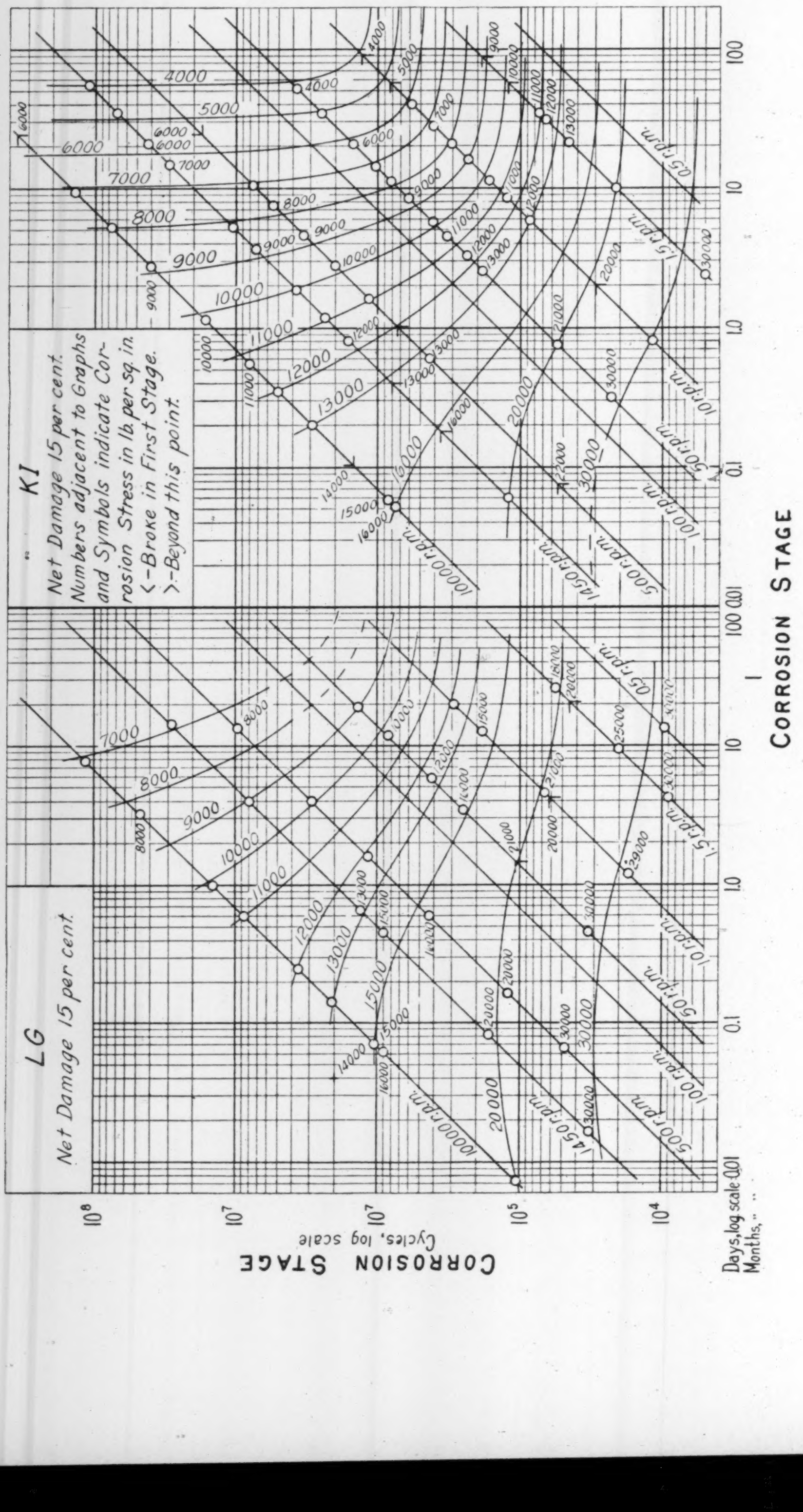

FIG. 6.—Type 10 Constant Net-Damage Diagrams, Duralumin.

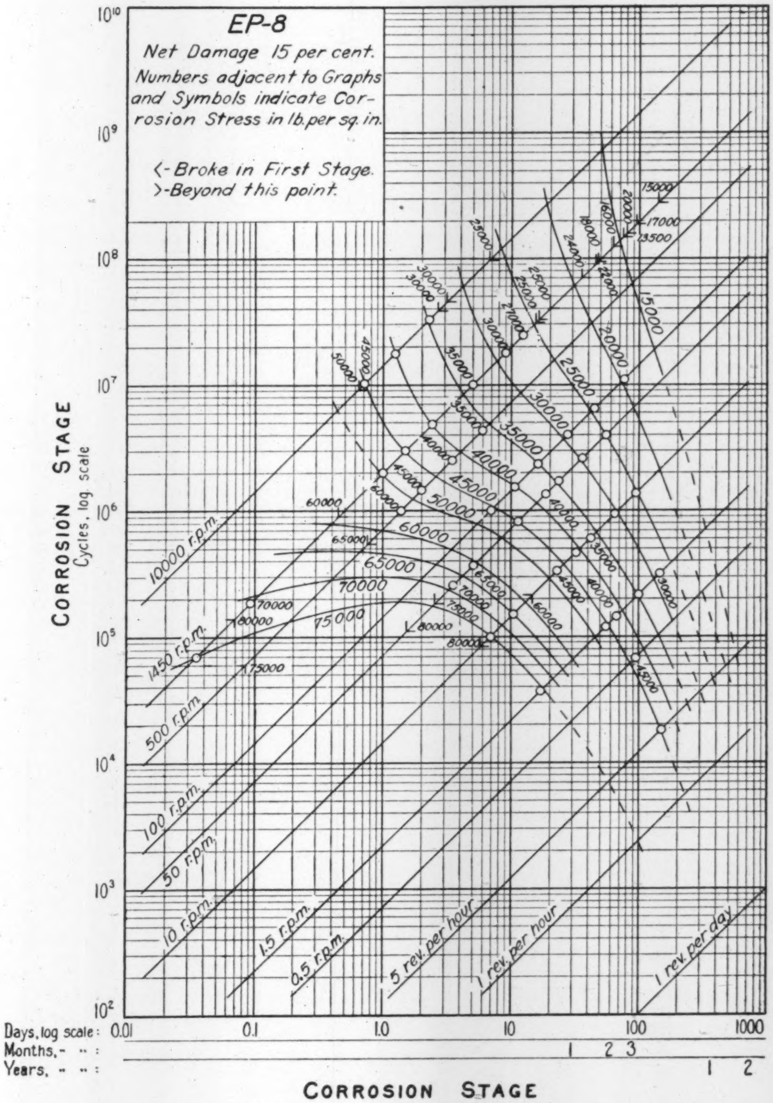

Fig. 7.—Type 10 Constant Net-Damage Diagram, Monel Metal.

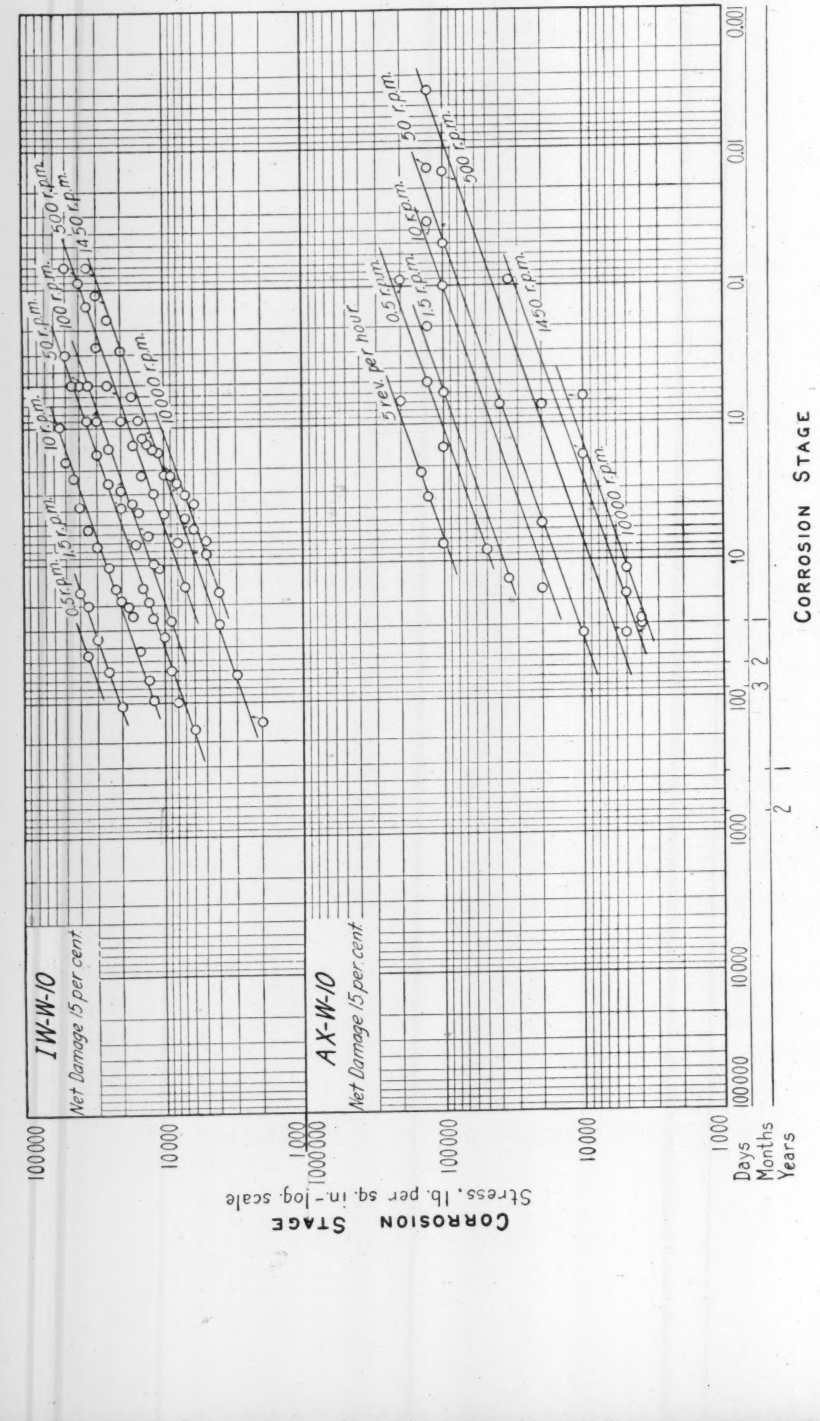

FIG. 8.—Type 11 (*a*) Constant Net-Damage Diagrams, Nickel Steel and Chromium-Nickel Steel.

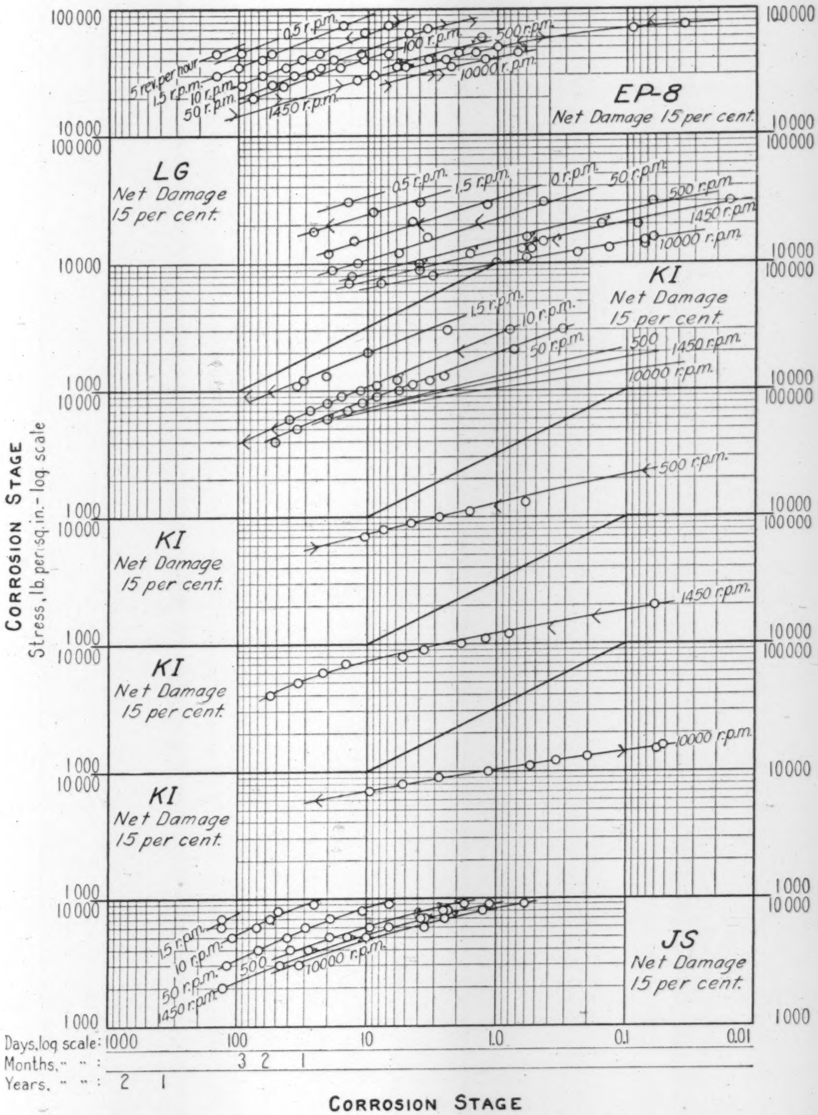

Fig. 9.—Type 11(*a*) Constant Net-Damage Diagrams, Monel Metal, Duralumin and Aluminum-Manganese Alloy.

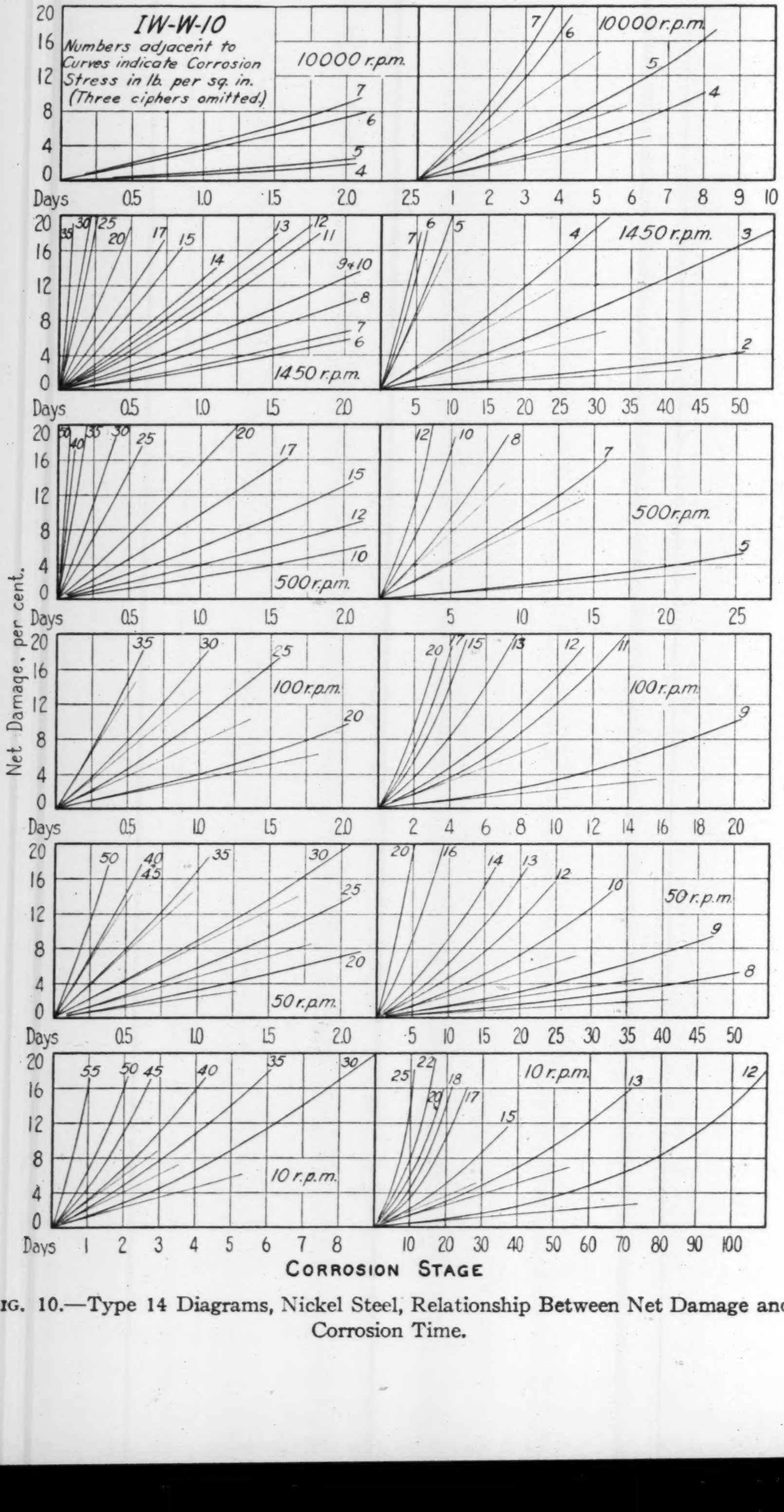

Fig. 10.—Type 14 Diagrams, Nickel Steel, Relationship Between Net Damage and Corrosion Time.

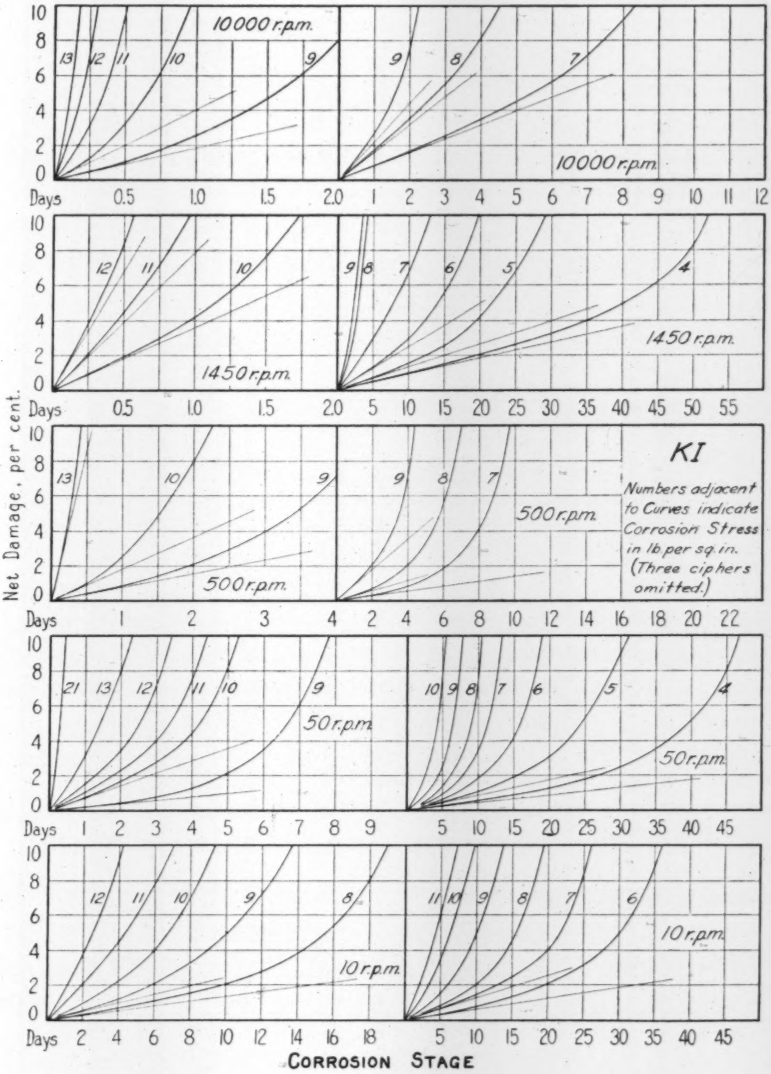

FIG. 11.—Type 14 Diagrams, Duralumin, Relationship Between Net Damage and Corrosion Time.

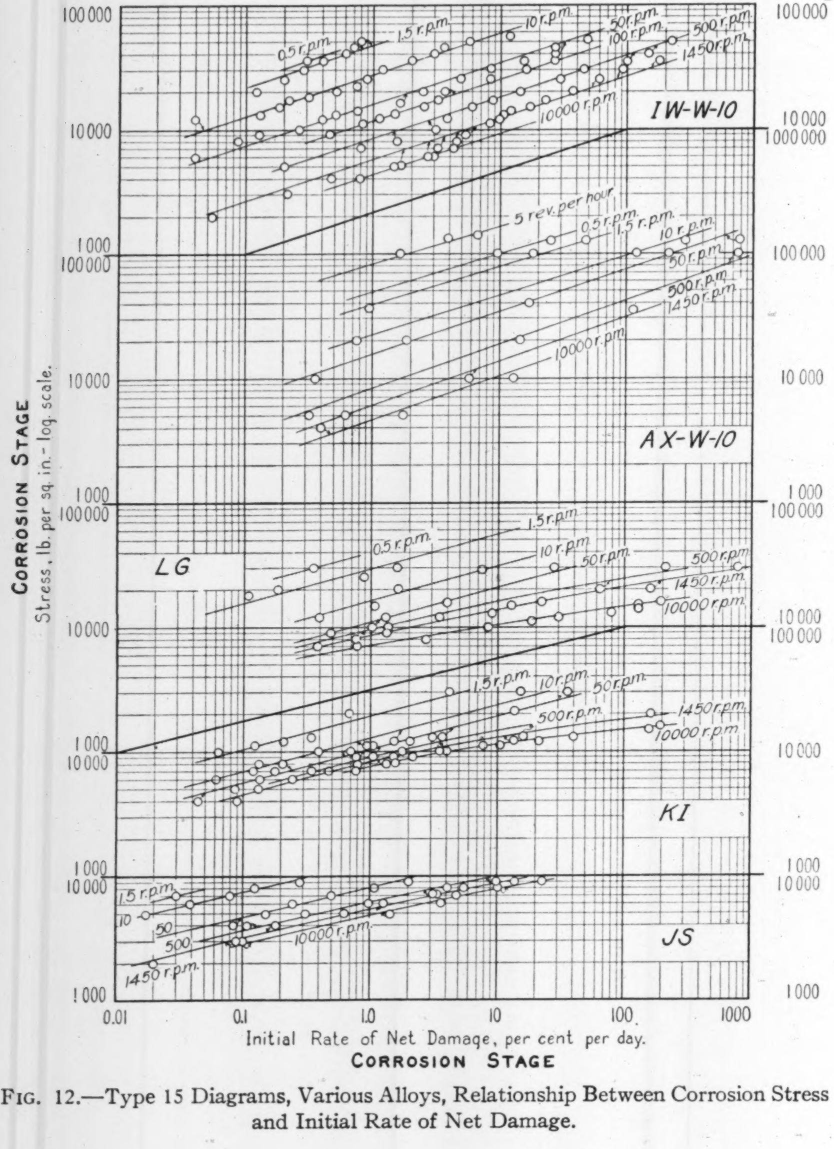

Fig. 12.—Type 15 Diagrams, Various Alloys, Relationship Between Corrosion Stress and Initial Rate of Net Damage.

DISCUSSION

MR. H. F. MOORE[1]—What strikes me as a very significant and very alarming fact is that when we get this corrosion factor tied on to fatigue, then the *time* element begins to loom up as important, and (I will be glad to have Mr. McAdam correct me if I am wrong) when we have ordinary fatigue tests without corrosion, the rate at which we make the test does not make very much difference, but when we get corrosion it is going to make a lot of difference whether we make the test at a thousand cycles of stress per minute in the laboratory or at the rate of one cycle a day in a boiler.

I should like to give a brief report, qualitative in its nature, of some experiments just finished at the University of Illinois which bring out facts in regard to certain phases of corrosion-fatigue. The tests were on boiler steel stressed, not under reversed stress but one-way bending. Corrosion-fatigue diminished the endurance limit in air by about the same percentage as in the case of tests of the material under reversed stress. Another point of interest was that the corroding liquid in these tests at Illinois was treated water from the University boiler plant, treated so that it would *not* cause caustic embrittlement. It did cause corrosion-fatigue.

MR. U. R. EVANS[2] (*by letter*).—Like all Mr. McAdam's publications, the present paper records work of great importance and practical value. I desire only to make a few remarks on the "General Duscussion" of the results (Part VII of the paper).

Mr. McAdam states "Stress increases the corrosion rate by increasing the permeability or effective 'porosity' of the coating." I am in complete agreement, but it is possibly interesting to note that the penetration of a film may occur in two ways:

1. A limited number of *distinct* cracks or discontinuities may occur in the skin.

2. The film substance may be porous *per se* just in the way in which a collodion membrane is porous.

It might perhaps be urged that the second case is merely a special form of the first, in which the cracks become very numerous and very small; but the two forms of penetration appear to be distinct. If a strip of iron is heated at one end, the other remaining cold, so as to produce a film thick at one end and thin at the other, it is found that, on testing different parts of the iron with copper nitrate, deposition of copper occurs at the two ends, but not in the middle.[1] At the heated end where the film is thick and liable to spontaneous cracking, the failure appears to be of the first kind; at the unheated end, the film is porous and the failure seems to be of the second kind. The two types do not pass into one another, and the areas where they occur are separated by an area where neither type occurs.

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[2] Cambridge, England.

In recent quantitative work on film permeability conducted at Cambridge University (England), there is ample evidence of both types of permeability, and the results suggest that both types are favored by stress. The penetration of the smaller anions through the film on an aluminum anode (maintained by potassium chromate) is under some conditions "an occurrence discontinuous in time and space"; much of the penetration, which can be followed by fluctuations of current and potential, is due to distinct breakdowns which occur first at one place and then at another; only when these breakdowns occur very frequently and very close together is there an approximation to continuous penetration.[2] On the other hand, the penetration of iodine through a silver iodide film, which occurs during the superficial conversion of silver into iodide, seems to be a continuous phenomenon; the film substance is in its nature porous to iodine.[3] In the case of vertical steel strips partially immersed in sodium chloride solution, there is evidence of both types. The main corrosion starts at a limited number of distinct points, representing weak places in the original invisible oxide skin (the attack becomes general as the original skin disappears through undermining or otherwise); these points are far more frequent near the edges (where internal stresses remain as a result of the cutting) than elsewhere, and it is therefore clear that *stress aids the discontinuous breakdowns*. But when the attack has developed, and the anodic area has spread over the whole of the lower part of the specimen, interference colors appear on the predominantly cathodic zone near the water line, due to uniform leakage of iron chloride through the uncreacked film; this salt entering a part of the solution where alkali is already in excess, reacts as it emerges to form an adherent hydroxide layer, of sufficiently uniform thickness to give interference tints. The sequence of colors shows that the film becomes thicker at the points where discontinuous breakdowns of type 1 have occurred.[1] In other words, it would seem that *the uniform leakage through the continuous porous (uncracked) film is also aided by stresses,* which pull out the skin, keeping the pores open.

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[1] U. R. Evans, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Inst. Metals Division, p. 7 (1929).

[2] S. C. Britton and U. R. Evans, unpublished work.

[3] U. R. Evans and L. C. Bannister, *Proceedings*, Royal Soc., A, Vol. 125, p. 370 (1929).

It may be argued that these distinctions are of purely academic interest. Actually, however, they have a practical bearing on the results. Where the permeability is a uniform leakage through a continuous porous film, absolute reproducibility should be obtained between duplicate experiments, provided the conditions are kept constant and the material is truly the same in all experiments. On the other hand, where the breakdown occurs at a limited number of distinct fissures, "probability considerations" enter into the matter, such as I have discussed elsewhere,[2] and a divergence between duplicates is to be expected—however carefully the conditions are controlled. The "scatter" obtained between experimental results, to which McAdam occasionally refers in his work, suggests that the applied stresses cause discontinuous film-cracking of type 1, in addition to an increase in the true porosity of type 2.

MR. D. J. MCADAM JR.[3] (*author's closure by letter*).—Mr. Evans in his discussion has given valuable information about the two ways in which the film may be penetrated. His conclusion that both types of penetration are favored by stress seems entirely logical. The amount of "scatter" obtained in fatigue-corrosion experiments, however, can hardly be used as a basis for deciding which type of penetration predominates. Stress concentration at the bottoms of corrosion pits is an erratic factor entering into all fatigue-corrosion experiments. In "duplicate" experiments, therefore, actual average corrosion stresses cannot be kept the same, and may differ greatly. For this reason some scatter would be expected, whether the original predominant film penetration is of the first or second type.

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[1] U. R. Evans, *Journal*, Chemical Soc., p. 111 (1929).

[2] U. R. Evans, Am. Electrochemical Soc., May Meeting, 1930.

[3] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

A STUDY OF THE ERROR OF AVERAGES AND ITS APPLICATION TO CORROSION TESTS

By C. H. Humes,[1] R. F. Passano,[2] and Anson Hayes[3]

Synopsis

In this paper there is presented a method of obtaining the required number of observations for a desired accuracy in the mean of the experimental data. This method assumes that the data show no evidence of an assignable cause of variation. The problem is then approached through the following procedure:

1. Determining the distribution characteristics of the universe, that is, the standard deviation.
2. Selecting the chance of success or failure which is reasonable.
3. Choosing the least difference from the mean of the universe (as average life of metal samples, tensile strength, etc.) which will be tolerated.

On these assumptions, the required number of observations are determined by the methods of statistics.

In an earlier paper by Passano and Hayes[4] it was shown that the distribution of failures in the immersion tests carried out by the Society's Committee A-5 on Corrosion of Iron and Steel approximated that required by the normal probability curve. It was stated, as a conclusion of that paper, that an investigation to determine the lives of materials must involve an adequate number of samples. No attempt was made at that time to state the sample size which would be considered an adequate number. It is the purpose of the present paper to approach the matter of sample size by the application of probability theory.

It is not implied that the authors are attempting to develop a new mathematical theory. In their work it has often become necessary to use the principles of statistics. Certain phases of these operations have come within their consciousness and they hope that by this discussion the portion which bears on the problems of this Society may become useful to some individuals without the difficulties which existed for the authors.

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[3] Director of Metallurgical Research, The American Rolling Mill Co., Middletown, Ohio.

[4] R. F. Passano and Anson Hayes, "A Method of Treating Data on the Lives of Ferrous Materials," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 220 (1929).

It is obvious that if all samples of a material failed at the same time, only one sample would be required to define the properties of that material in those conditions. If, on the other hand, the failures of the various samples occurred over a time range, some larger number would be required to produce a satisfactory result. Furthermore, the greater the time interval over which failures occur in a given service condition, the larger is the sample size required to give a true measure of service.

The statements of the preceding paragraph mention two essential functions. They are the average and the range of time over which failures occur. To approach the problem, these two characteristics of a universe must be stated more precisely. First, the average or arithmetic mean, which is defined as the sum of the individual observations, X_i, divided by the number of observations, n,

$$\overline{X} = \frac{\sum\limits_{i=1}^{n} X_i}{n} \tag{1}$$

and, second, a measure of the spread, namely, the standard deviation, σ, which is defined as the square root of the average square minus the square of the average:

$$\sigma = \sqrt{\frac{\sum\limits_{i=1}^{n} (X_i - \overline{X})^2}{n}} = \sqrt{\frac{\sum\limits_{i=1}^{n} X_i^2}{n} - \overline{X}^2} \tag{2}$$

It is the standard deviation which describes the manner in which the individual values are distributed about the arithmetic mean $\overline{X}$.

If the standard deviation σ' of the universe is known from previous observations, the standard deviation $\sigma_{\bar{x}}$ of the sample of size n can be calculated from the relation:

$$\sigma_{\bar{x}} = \frac{\sigma'}{\sqrt{n}} \tag{3}$$

The probability that an observed average, $\overline{X}$, of a sample of size n, will fall within the range of $\overline{X}$ to $\overline{X} + d\overline{X}$ is given by the expression:

$$dP = \frac{\sqrt{n}}{\sigma'\sqrt{2\pi}}\, e^{\frac{-n(\overline{X}-\overline{X}')^2}{2\sigma'^2}}\, d\overline{X} \tag{4}$$

So long as the variable X is controlled by a constant system of chance causes,[1] the distribution of samples of size n from that universe will approach normal distribution. The probability that the average of samples of size n will differ from the mean of the universe by a fixed amount can be obtained from a table giving values of the probability integral. These tables are constructed on the basis of the variable z to which the standard deviation $\sigma_{\bar{x}}$ of the sample of size n, and the fixed amount $\bar{X} - \bar{X}'$ are related by the equation:

$$z = \frac{\bar{X} - \bar{X}'}{\sigma_{x}} = \frac{(\bar{X} - \bar{X}')\sqrt{n}}{\sigma'}$$

Since there is one value given in the integral table for every value of the probability P, it is evident that knowing the standard deviation σ' of the universe, it is possible to solve three problems:

1. What is the probability P that the average of a sample of size n drawn from a constant system of chance causes will lie between the limits $\bar{X}' \pm x$ where $x = \bar{X} - \bar{X}'$?

2. What is the value of x such that an average $\bar{X}$ of n observations will have a given probability P' of lying between the limits $\bar{X} \pm x$?

3. What sample size must we use in order that there will be the probability P' of the average lying between the limits $\bar{X}' \pm x$?

For many years the immersion tests of Subcommittee V of the Society's Committee A-5 have been under observation. For the purposes of illustration it seems most natural to choose material with which the Society is familiar. The following treatment is based on two sections of that evidence, namely, the failures of No. 22 and No. 16 gage sheets in Washington tap water.

The two selected universes are characterized by the statistics given below:

	$\bar{X}'$	σ'
No. 22 gage sheets	874.89	85.31
No. 16 gage sheets	1940.18	224.14

Problem 1.—To find the probability that the average of a sample of size n taken from these universes will lie within x days of the mean.

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[1] W. A. Shewhart, "Basis for Analysis of Test Results of Die-Casting Alloy Investigation," Report of Subcommittee XV, Committee B-2, Appendix I, *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 200 (1929).

Let $x = 50$ days
and $n = 25$

It is known that $$z = \frac{x\sqrt{n}}{\sigma'}$$

for No. 22 gage sheets $$z = \frac{50 \times \sqrt{25}}{85.31} = 2.930$$

for No. 16 gage sheets $$z = \frac{50 \times \sqrt{25}}{224.14} = 1.115$$

Values of P taken from tables given in Rietz' "Handbook of Mathematical Statistics," are as follows:

for No. 22 gage sheets, $0.498305 \times 2 = 0.996610$
for No. 16 gage sheets, $0.367572 \times 2 = 0.735144$

In the case of No. 22 gage sheets, there are approximately 997 chances in 1000 that the average of a sample size of 25 will lie within 50 days of the average of the universe, but, in the case of the No. 16 gage sheets, the chances of an average of 25 specimens lying within 50 days of the average of the universe are only 7 out of 10 approximately.

Problem 2.—To determine the value of x such that an average of a sample of size n will have a probability P' of lying within the limits $\overline{X} \pm x$.

Let $P' = 0.9000$
from the tables $z = 1.645$
Let $n = 25$

for No. 22 gage sheets $$1.645 = \frac{x\sqrt{25}}{85.31}$$

$$x = \frac{1.645 \times 85.31}{5} = 28.05$$

for No. 16 gage sheets $$1.645 = \frac{x\sqrt{25}}{224.14}$$

$$x = \frac{1.645 \times 224.14}{5} = 73.75$$

These results are shown graphically in Fig. 1; the figure also shows the error of an average for samples of varying size.

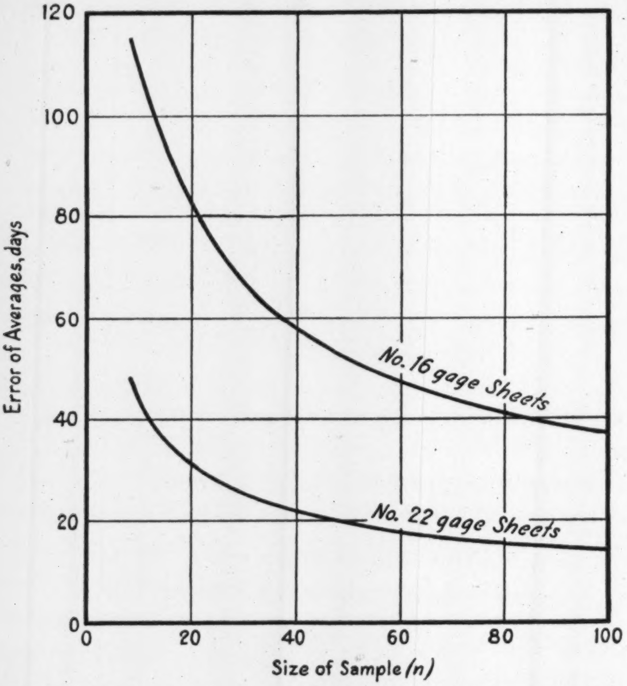

FIG. 1.—Calculated Error of an Average of Samples of Size n, the Probability of the Error not Exceeding the Given Value Being 0.9. Tests in Washington tap water.

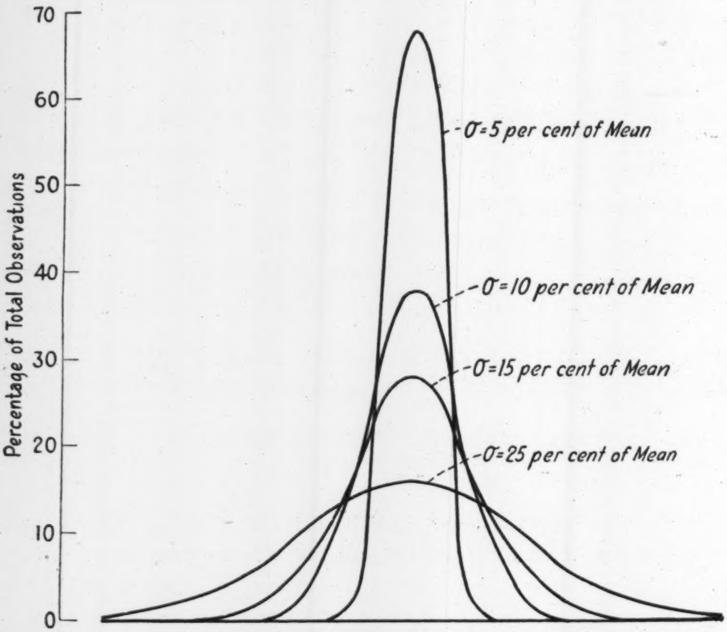

FIG. 2.—Distribution Curves of Normal Universes, the Standard Deviations of Which are Expressed as Percentages of the Means of These Universes.

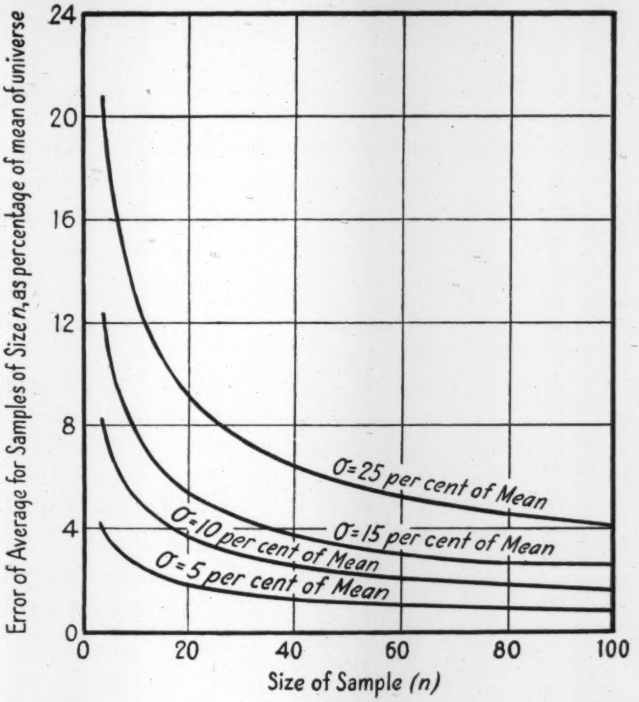

FIG. 3.—Percentage Error of Averages for Samples of Size *n* when the Standard Deviation is Expressed in Percentage of the Mean of the Universe and the Probability for not Exceeding Which is 0.9.

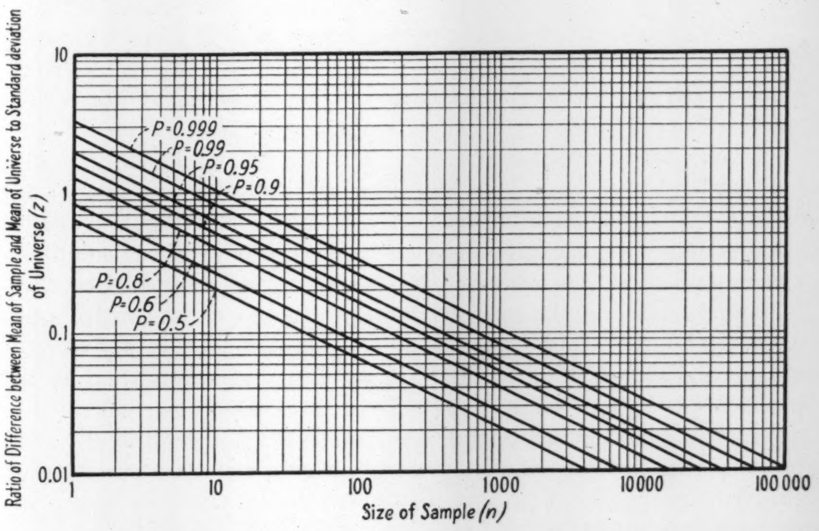

FIG. 4.—Size of Sample to be Taken from a Normal Universe in Order to Obtain a Given Probability of a Desired Accuracy for a given Standard Deviation of the Universe.

When the standard deviation of the universe σ is known, calculate *z* which is the quotient of the error that will be tolerated, divided by the standard deviation. Using the curve corresponding to the desired probability of not exceeding this difference, read the value of *n*.

NOTE.—The standard deviation of this figure is the standard deviation of the universe and not the standard deviation of the average.

Problem 3.—To determine the value of n for a future test such that there will not be more than 1 chance in 10 of the average of sample of size n being in error by more than 5 per cent of the average of the universe.

$$P = 0.9000$$
$$z = 1.645$$

for No. 22 gage sheets $x = \frac{847.89}{20} = 43.75$

$$1.645 = \frac{43.75\sqrt{n}}{85.31}$$

$$\sqrt{n} = 3.21$$
$$n = 10.3$$

for No. 16 gage sheets $x = \frac{1940.18}{20} = 97.01$

$$1.645 = \frac{97.01\sqrt{n}}{224.14}$$

$$\sqrt{n} = 3.81$$
$$n = 14.5$$

There would be required 10 samples of No. 22 gage sheets and 15 samples of No. 16 gage sheets if the chances of the error of the average differing from the average of the universe by more than 5 per cent are 1 in 10.

From these computations, it is seen that the standard deviation is an important statistic. It is, therefore, desirable to consider this statistic in greater detail than is the custom. In planning future experiments, one must have some *a priori* knowledge of the conditions or be in a position to estimate a likely value for the standard deviation. The more uniform is the service condition the less is the spread anticipated. Thus it may be that if the standard deviation is expressed as a percentage of the arithmetic mean, a series of small values will be observed. After some experience with atmospheric, underwater, underground, and more complicated services of sheet metal, it has appeared that failures are distributed in such a way that the standard deviations encountered lie generally between 5 and 30 per cent of the arithmetic mean.

In Fig. 2 are shown calculated distribution curves for such a range of standard deviations, and, in Fig. 3 are shown the number of samples necessary to obtain a given accuracy expressed as a percentage of the mean when the probability of success is assumed to be 9 out of 10.

This is extended in Fig. 4 to cover many probabilities from which figure it is possible to solve problems of the three types above, if the standard deviation of the universe can be assumed known.

Acknowledgment.—For the symbols, theoretical background, and friendly criticism and assistance, the authors wish to express their gratefulness to Mr. W. A. Shewhart, and Mr. F. W. Winters, of the Bell Telephone Laboratories, Inc.

Mr. R. L. Kenyon has assisted in the application of the theory to many concrete problems and is responsible for Fig. 4 of this paper; to him we are also indebted.

SOME OBSERVATIONS ON THE OUTDOOR ATMOSPHERIC CORROSION OF PROTECTIVE ZINC COATINGS

By C. L. Hippensteel,[1] C. W. Borgmann,[1] and F. F. Farnsworth[1]

Synopsis

An investigation was undertaken to obtain a better picture of outdoor atmospheric corrosion of protective zinc coatings of the hot-dipped type on iron and steel and was undertaken for the purpose of developing an accelerated laboratory test to judge the serviceability of these coatings. This report of progress contains the results of controlled outdoor exposure tests in New York City. Test panels of the coatings under study were exposed in one case under the normal conditions of the location and in another case under somewhat modified conditions. Periodic weighings and visual examinations were made. The performance of the coatings was also studied in a type of accelerated laboratory test and the results reported.

No appreciable change in rate of loss of weight was found as the zinc and zinc-iron alloy layers of hot-dipped coatings became successively attacked on outdoor exposure. Also no difference between the rate of loss of weight for the hot-dipped, heat-treated hot-dipped, or sherardized coatings was observed. The rate of corrosion of these coatings was found to be similar to that for two grades of rolled zinc. The accelerated laboratory test did not show the same similarity in rates of loss of weight of these different types of coatings as obtained under the particular outdoor exposures reported.

Introduction

Several years ago the authors studied the corrosion which had taken place on specimens of hot-dipped[2] hardware which had been in service for various periods of time in New York City and its suburban districts. Other samples from the same lots of hardware had been retained in storage and were used for determining an approximate average initial weight of coating. The rate of loss of weight of the coatings, determined by comparing the amount of zinc remaining after 3 and 6 years with the initial weight, was found to be from 3 to 5 mg. per sq. cm. per year with an apparent slowing down of the rate with time. However, as the variation in individual results was so large, no conclusions could be justified because of the limited number of samples tested and the lack of precise information regarding the conditions of exposure of the different lots of hardware. Consequently, it seemed desirable to carry out exposure tests under known atmospheric conditions and using materials of known history.

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[1] Bell Telephone Laboratories, Inc., New York City.

[2] In this paper the authors have used the following terminology in discussing zinc-coated materials. "Hot-dipped coating" is used to designate the type of coating applied on iron or steel by dipping in molten zinc. "Heat-treated hot-dipped coating" refers to that type of coating produced by heat treating a hot-dipped coating. "Sherardized coating," sometimes called "dry galvanized" or "vapor galvanized," is used to designate the coating formed on steel by the so-called cementation process of tumbling steel parts in a drum at an elevated temperature in intimate contact with a dust consisting primarily of zinc. The term "zinc-iron alloy layer" or "alloy layer" is used in a general sense to include that portion of the coating between the base metal and the outer layer of the coating consisting of relatively pure zinc.

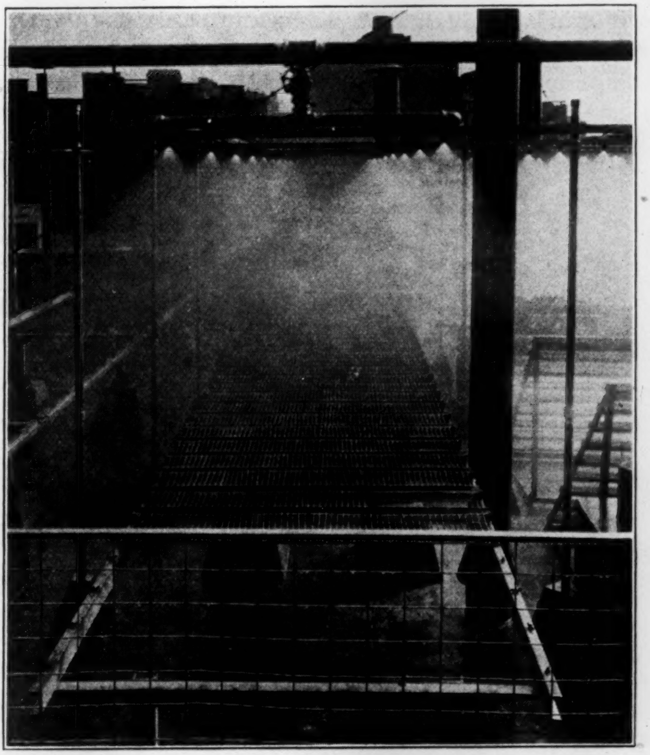

FIG. 1.—Showing Method of Spraying Specimens.

STUDY OF OUTDOOR ATMOSPHERIC CORROSION OF ZINC AND ZINC COATINGS

The outdoor exposure in the atmospheric tests was on the Hudson River in downtown New York City. The atmosphere in this location has been found to be highly industrial in character and severely corrosive. The sulfur dioxide content is considerably above that normally found in city atmospheres and a relatively high percentage of dust is present. This dust consists largely of carbonaceous matter, primarily cinders together with smaller percentages of soot and coal dust.

These particles add to the corrosiveness of the location in that they may form nuclei for local attack. The sea (2 miles distant) may add even another element to the severity of this atmosphere in the form of a relatively high chloride content.

In certain of the tests conducted in this atmosphere, the severity of the exposure was increased by spraying the specimens with water. (See Fig. 1.) This spray was used to simulate additional rainfall with the intention of obtaining a reasonable acceleration of the normal weathering. It was applied three times daily (except Sunday) for 15-minute periods during the eight months from April to December.

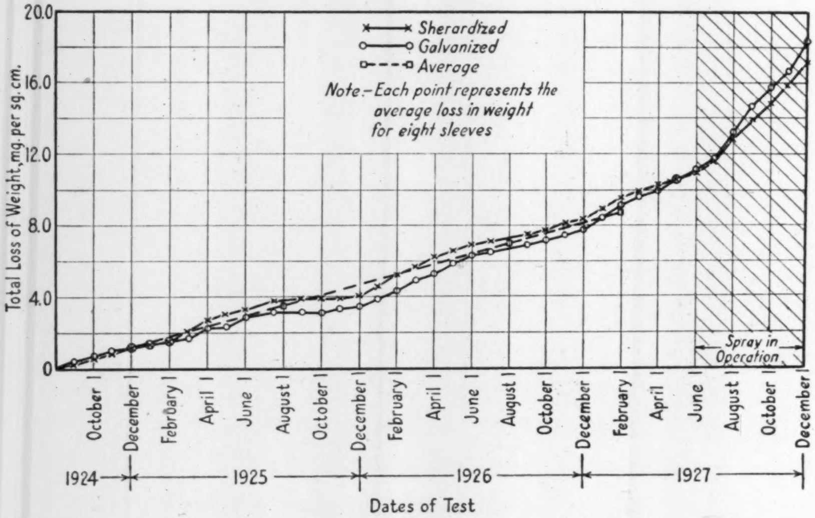

FIG. 2.—Showing Results of Weight Loss Measurements Made over a Period of 3½ Years.

The first of the quantitative outdoor tests was primarily an engineering study of the rates of weathering of hot-dipped and sherardized finishes, using short tubes, 1.28 cm. in outer diameter, 1.90 cm. long with a 0.32 cm. wall thickness as samples. Eight specimens each of hot-dipped and sherardized tubes were included in the test. Weight loss measurements which were made on these parts over a period of 3½ years are graphically shown in Fig. 2. It will be noted from the curves that there is no marked slowing down of the rate of loss of weight for either type of coating throughout the period of test. The weight loss rate for both during the first 2½ years was fairly constant at a value for loss in weight of 3.5 mg. per sq. cm. per year. The sharp break upward near the end of the curves is due to the accelerating effect of the water spray used to simulate rainfall which was first started on the date indicated on the chart. Where slight variations are to be noted, due to seasonal changes, both types of coating react in the same manner. No difference is shown between the initial outdoor corrosion rates of the relatively pure zinc outer layer of a hot-dipped coating and of the zinc-iron alloys which are the essential constituents of a sherardized coating. As alloy layer rust had appeared on the hot-dipped specimens after about two years of exposure and as no change in rate had occurred, it may be concluded that there is no difference in the weathering rate for the outer zinc and the inner alloy layers. Lastly, there appears to be no difference between the rates for the zinc-iron alloy layers of hot-dipped and sherardized coatings.

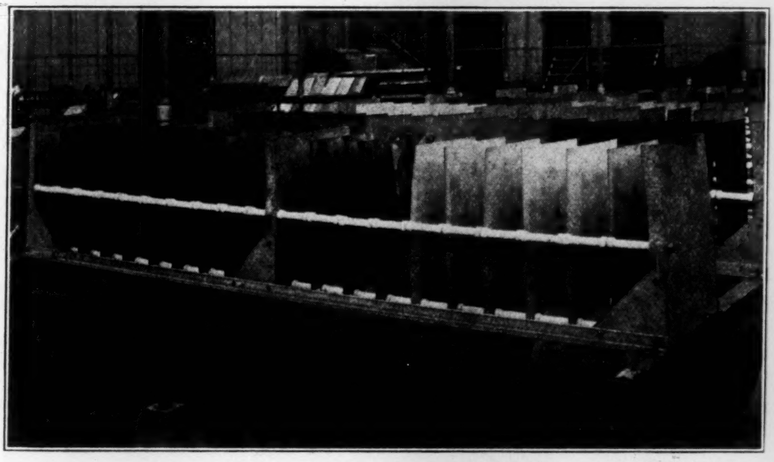

FIG. 3.—Showing Sheets Mounted for Controlled Outdoor Exposure.

A second series of controlled outdoor exposure tests was started using sheets of (1) commercially prepared hot-dipped steel, (2) heat-treated hot-dipped steel, (3) sherardized steel, (4) rolled high-grade zinc, and (5) rolled prime western zinc. The test panels used were 22.9 by 30.5 cm. (9 by 12 in.) in size. Six test panels of each material were exposed at each of the two outdoor roof exposures mentioned above.

The specimens were mounted vertically as shown in Fig. 3, between four hot-dipped rods and were spaced 3 in. apart by means of special porcelain knobs. This arrangement permitted the exposure of all panels in a given rack to identical conditions. The racks were all similarly oriented.

The cut edges of the test panels, where necessary, were grit-blasted and coated with zinc by spraying with a Schoop gun. In preparing these panels they were clamped together with the cut edges slightly staggered to prevent the sprayed edges from being damaged when the panels were subsequently separated.

All specimens, before exposure, were cleaned thoroughly with acetone to remove all traces of grease. Cotton gloves were used during handling of the specimens to guard against contamination of the surface of the panels during the weighings which were made at intervals of 2 months.

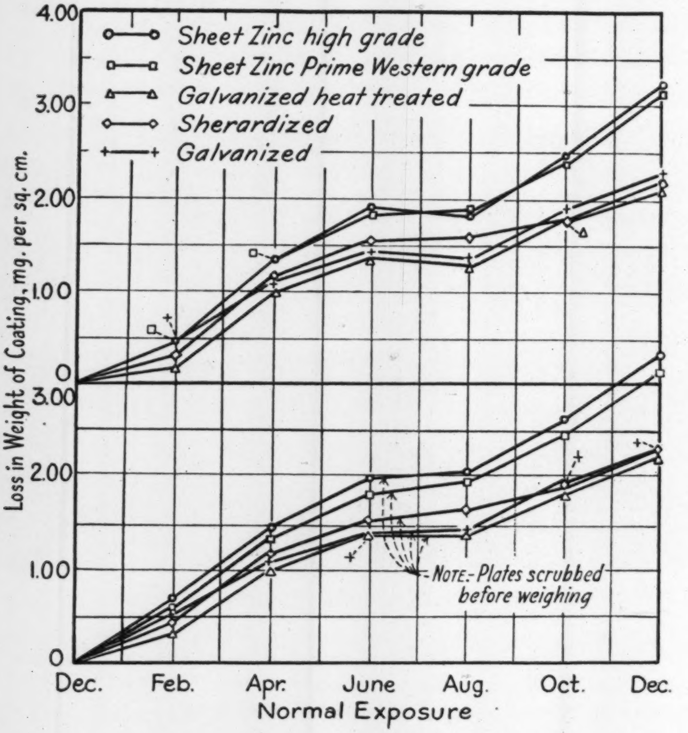

FIG. 4.—Showing Loss in Weight Results During One Year of Unmodified Outdoor Exposure.

In order to check the effect of the method of cleaning the panels before weighing, three of the six test panels from each exposure were scrubbed with a stiff bristle brush under running water, and the other three were given only a light brushing with a soft bristle brush to remove whatever dirt or dust was clinging to the surface. However, the results show that this variation in treatment of the surface has had only a small effect[1] on the rate of loss of weight of the coatings or of the zinc sheet.

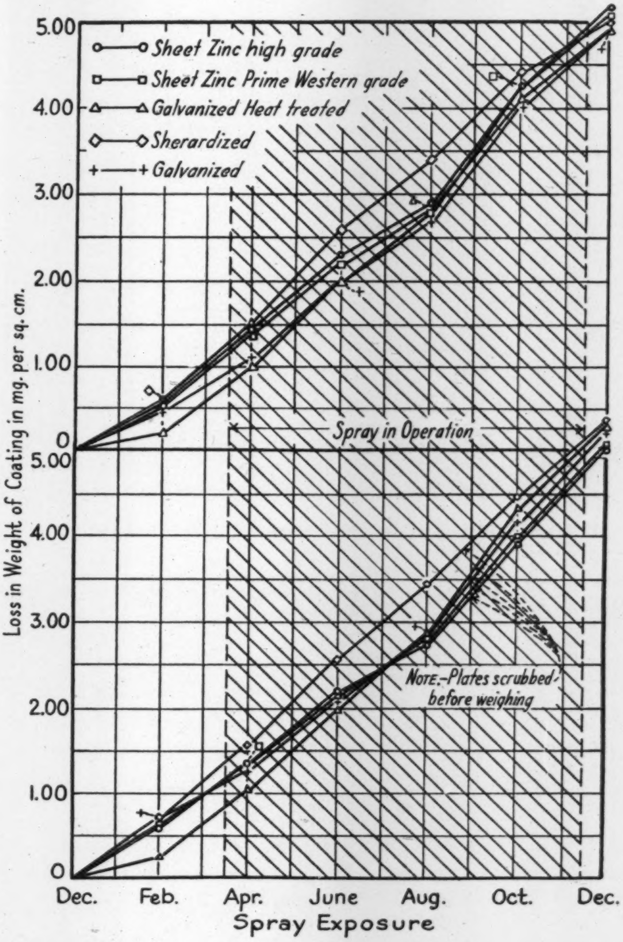

FIG. 5.—Showing Loss in Weight Results During One Year of Outdoor Exposure, Supplemented by Spraying.

Figures 4 and 5 show respectively the loss in weight results during one year of unmodified outdoor exposure and outdoor exposure supplemented by spraying. Each point on the curves is the average of three closely agreeing values. The tests were begun during December when the spray was not in operation, and the results of the first four months from both test racks check closely, which indicates that other than the spray there is very little difference between the exposures. However, as can readily be seen, the coatings exposed on the sprayed test rack lost weight much faster than did those on the normal exposure test rack, during the spray period.

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[1] This shows that the rate of loss in weight as determined may be considered a close approximation of the actual rate of corrosion. This is further substantiated by a microscopical examination which indicated that the amount of corrosion products retained on the samples was relatively small.

In the normal exposure the zinc sheets lost weight somewhat faster than did the three zinc coatings, the rate for the latter being approximately 2.5 mg. per sq. cm. per year. Under the spray exposure, the rates of corrosion of all five types of panels agree quite closely, the value being somewhat more than 5.0 mg. per sq. cm. per year. So far, this test does not indicate a substantially different rate of corrosion for zinc or zinc-iron alloy.

Studies are being made on one plate of each type of coating included in the above tests to determine the compositions and amounts of corrosion products remaining at the end of the year's exposure. Also the total metallic coating remaining after one year exposure is being determined as a means of obtaining further information on the mechanism of corrosion of zinc coatings in industrial areas. The results of these studies will be reported at a later date.

OBSERVATIONS MADE DURING THE WEATHERING OF THE ZINC COATINGS

In determining the protective effect of zinc coating on steel, the uniformity of coating must be considered in judging the service life of a given weight of coating. Our observations of the hot-dipped coatings as they weathered soon showed that they were not of uniform thickness. The thickness varies on these coatings because of an uneven flow of the solidifying zinc clinging to the surface as the object being coated is withdrawn from the molten zinc bath. Also the familiar roll marks, resulting from the drawing of the sheet through the zinc bath by means of grooved rollers, became apparent on the surface of the sheet as corrosion proceeded. The variations in thickness of coating are illustrated in Figs. 6 and 7. Figure 6 shows the roll marks, above mentioned, as light bands spaced at equal distances apart and running across the sheet. Figure 7 illustrates the usual appearance of weathered hot-dipped sheet; the spangles are still apparent in some of the light colored areas, while the dark portions show the presence of alloy layer. These variations in the thickness of coating seem to be relatively more marked as the weight of coating increases.

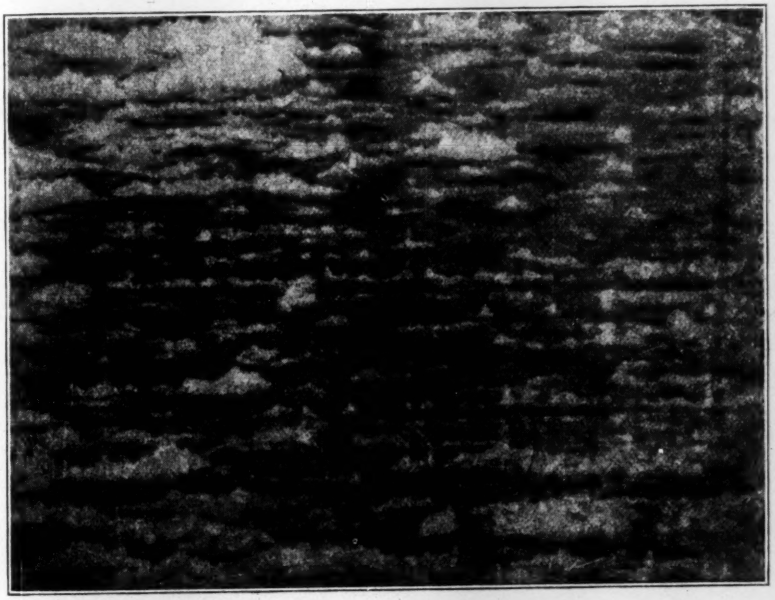

FIG. 7.—Showing Usual Appearance of Weathered Hot-Dipped Sheet.

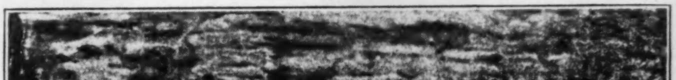

FIG. 6.—Showing Roll Marks Resulting from Drawing the Sheet Through the Zinc Bath by Means of Grooved Rollers.

There has been considerable discussion concerning the possibility that the edges of the spangles of hot-dipped sheets may constitute areas of first failure. In this connection it was observed that on sheets carrying a relatively heavy hot-dipped coating (approximately 38 mg. per sq. cm.) alloy rust appeared first at the edge of the spangles. This is shown in Fig. 8 which is a photograph, taken at 2 diameters but reduced in reproduction, of a galvanized sheet with the above weight of coating after 4 years of exposure on the roof. A similar phenomenon, however, has not been observed by the authors on sheets carrying a lighter coating.

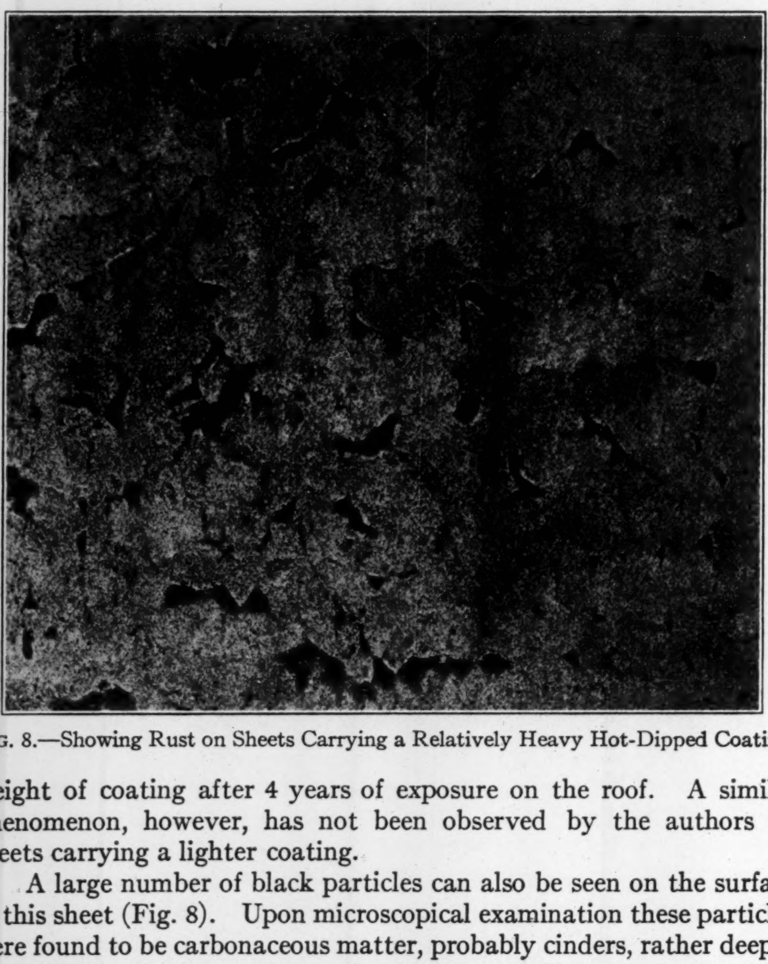

FIG. 8.—Showing Rust on Sheets Carrying a Relatively Heavy Hot-Dipped Coating.

A large number of black particles can also be seen on the surface of this sheet (Fig. 8). Upon microscopical examination these particles were found to be carbonaceous matter, probably cinders, rather deeply embedded in the layer of corrosion products. These cinder particles no doubt have an accelerating effect on the corrosion rate because of galvanic couple action and their influence on the weathering rate remains a problem for further investigation.

Independent of the observations on the similarity of rates of loss of weight of continuous zinc or zinc-iron alloy coatings exposed outdoors, the question arises as to whether or not their relative electrochemical protective effects, in cases where base metal is exposed, will be of enough importance to modify opinions based solely on the rates of weathering of these coatings. Zinc protective coating may be effective in two ways, namely, by affording protection as a result of a continuous envelope of metal or by an electrochemical protection in case this envelope is not continuous. If the coating is continuous, then the rate at which it is attacked is the only factor. If the coatings are not continuous initially or if they become discontinuous due to the weathering of a coating of non-uniform thickness, then the electrochemical properties of the finish and the underlying metal, as well as the rate of attack of the coating, must be taken into consideration in the evaluation of the protective zinc coating. Bauer[1] has shown that in very weak electrolytes, as would obtain in outdoor conditions, the electrochemical relationships are such, in the case of zinc and iron, that the protection of the zinc can only be effective over very minute exposed areas of the underlying iron. Our experience leads us to agree with Bauer that zinc coatings by virtue of these relationships cannot be relied upon in normal atmospheric exposures to prevent corrosion occurring in sizeable mechanical defects in the coating. But on the other hand zinc coatings will not tend to accelerate the corrosion of exposed areas of base metal as will coatings of metals electropositive to iron. However, it is an observed fact that corrosion of iron is delayed in fine hair line cracks produced by bending a zinc-coated material.

ACCELERATED LABORATORY TESTS USING A ROTATING ALTERNATE IMMERSION APPARATUS

Studies were undertaken in the laboratory with a view to developing an accelerated corrosion test which would simulate the results of the outdoor exposures. Some experience had previously been gained in the use of an intermittent immersion test for visually characterizing electroplated zinc coatings described in a paper by Farnsworth and Hocker.[2] They suggested that such a test might be useful in the testing of hot-dipped coatings. Experiments along this line, however, showed that weight loss determinations of the rate of corrosion could not accurately be made because of the presence of a "drain area" at the bottom of the test specimen during the drying cycle, which abnormally accelerated the corrosion in that area. A modified form of this test was developed to eliminate this "drain area" and thus make these measurements possible. In this, specimens were attached to the outer ends of a wheel rotating at the rate of 1 r.p.m. During each revolution the specimens were immersed in a dilute aqueous solution of ammonium chloride for approximately 5 seconds and allowed to be in contact with the humid air above the solution for the remainder of the cycle. This modification introduced another change in the testing conditions, namely, that the specimens were continuously wet with solution.

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[1] O. Bauer, *Mitteilungen*, Material Prüfungs Anstalt, 1918, p. 114.

[2] F. F. Farnsworth and C. D. Hocker, "*Transactions*, Am. Electrochemical Soc., Vol. XLV, p. 281 (1924).

TABLE I.—RESULTS OF ROTATING ALTERNATE IMMERSION CORROSION TESTS ON HOT-DIPPED, HEAT-TREATED HOT-DIPPED, AND ZINC SHEET MATERIALS.

Sheet Material	Description	Loss of Weight, mg., per sq. cm.					
		First Day	Second Day	Third Day	Fourth Day	Fifth Day	Sixth Day
Zinc	Rolled High-grade Zinc	6.1	6.1	5.7	4.5	5.3	...
Zinc	Extruded High-grade Zinc	7.5	6.6	7.6	6.4	6.8	...
Zinc	"Chemically Pure," rolled	6.6	6.0	5.6	4.6	4.5	...
Zinc	Rolled Prime Western Zinc	6.2	5.8	6.5	4.7	4.5	...
Hot-Dipped Iron	No. 1 – Initial Weight of Coating, 37.2 mg. per sq. cm	8.3	3.3[a]	1.6	1.2	1.3	1.1
Hot-Dipped Iron	No. 2	7.4	2.9[a]	1.6	1.5	1.4	0.8
Hot-Dipped Iron	No. 3	8.3	4.1[a]	1.7	...	...	...
Hot-Dipped Iron	No. 4	6.8	3.3[a]	1.5	...	...	...
Hot-Dipped Iron	No. 5, Initial Weight of Coating, 19.1 mg. per sq. cm.	6.9	5.1	2.0[a]	1.6	1.4	...
Heat-Treated Hot-Dipped Iron	No. 1, Initial Weight of Coating, 27.0 mg. per sq. cm. Same sheet as No. 5 but heat-treated	4.8	3 2[a]	3.0	1.7	1 9	...

[a] Alloy rust color appeared on this day.

TABLE II.—RESULTS OF ROTATING ALTERNATE IMMERSION CORROSION TESTS ON HOT-DIPPED IRON AND ZINC WIRE MATERIALS.

Wire Material	Description	Loss of Weight, mg. per sq. cm.					
		First Day	Second Day	Third Day	Fourth Day	Fifth Day	Sixth Day
Zinc Rod	High-grade Zinc, shaped similar in cross-section to cable ring	12.7	10.2	10.1	10.1	10.0	10.5
Cable Ring	No. 1, Lot B. Stored specimen. Initial Coating 38.2 mg. per sq. cm	11.7	13.8	Removed for examination.			
Cable Ring	No. 2, Lot B. Same as No. 1. Initial Coating 50.8 mg. per sq. cm	11.7	12.5	9.7	4.3	....	....
Weathered Cable Ring	No. 3, Lot B. $3\frac{1}{6}$ years exposure. Residual coating 32.4 mg. per sq. cm	10.0	10.1	Removed for examination.			
Weathered Cable Ring	No. 4, Lot B. $3\frac{1}{6}$ years exposure. Residual coating 30.8 mg. per sq. cm	11.4	11.3	7.9	2.9	3.1	....
Weathered Cable Ring	No. 5, Lot C. 6 years exposure. Residual coating 23.1 mg. per sq. cm	2.5	0.9	Removed for examination.			
Weathered Cable Ring	No. 6, Lot C. 6 years exposure. Residual coating 26.3 mg. per sq. cm	4.6	3.4	2.9	1.3	0.8	0.6
Weathered Cable Ring	No. 7, Lot C. 6 years exposure. Residual coating 22.3 mg. per sq. cm. This ring was dipped in dilute HCl before each weighing	6.8	6.5	5.0	3.6	2.5	....
Hot-Dipped Wire No. 8 B. & S. Gage	Initial Coating 36.2 mg. per sq. cm	9.7	9.0	7.3	8.5	2.9	1.0
Hot-Dipped Wire No. 8 B. & S. Gage	Initial Coating 32.6 mg. per sq. cm	7.9	9.0	4.8	1.3	1.6	1.1

Using this test a study was made of the corrosion rates for hot-dipped sheet, heat-treated hot-dipped sheet, various grades of sheet zinc (rolled and extruded), cable rings (hardware referred to in the introduction) from the lots reported upon above, zinc rod (similar in cross-section to a cable ring), and hot-dipped wire. The results of these tests are given in Tables I and II.

A study of these results reveals several points of interest. It can be seen in Table I that the corrosion rate of a hot-dipped coating on sheet material in the rotating alternate immersion test decreased with time, there being quite a sharp break in the rate coincident with the appearance of alloy layer rust. Also by comparing the test results on a heat-treated hot-dipped coating with those on hot-dipped coatings it is seen that the former has a lower initial rate than the latter. As the coating formed in the heat-treating process consists mainly of zinc-iron alloys, these data further substantiate the observation that in this test the zinc-iron alloys found in hot-dipped coatings corrode at a slower rate than does the relatively pure zinc outer layer. In this table it will be seen that there is but little difference in the rate of weight loss for the three rolled zinc sheets, and that the extruded specimen has a somewhat higher rate of loss, comparable with the initial rate for hot-dipped coatings. A significant observation to be made from these data is that in this test the rate of corrosion of zinc does not slow down appreciably with time as does that for hot-dipped sheets.

In Table II are given the data collected in this test on wire materials. The hot-dipped coating on wire, such as on cable rings, had a much higher initial rate of corrosion than was found on the coated sheets. The possible effect of size or shape of the sample, corroded in this type of test, on the rate of weight loss is discussed in a later paragraph. On these wire materials, the coating again shows a marked decrease in corrosion coincident with the exposure of the alloy layers. This is true whether the test was made on stored or weathered cable rings. The rate of corrosion of the hot-dipped wire was found to be of the same order as that of cable rings, with a similar slowing down at the time of exposure of the alloy layers. The rate at which a cable ring (No. 6), previously weathered outdoors for 6 years, lost weight in this test was considerably lower than that obtaining for a new ring. This ring had weathered well down into the alloy layers. A second ring (No. 7) from the same lot was given a quick acid dip to remove corrosion products and run in comparison with ring No. 6. It will be noted that while the rate of loss of weight of the acid-dipped specimen was slightly higher than that for the other, it still was appreciably lower than that for unweathered rings or zinc wire similarly shaped. Consequently, it could be inferred from this data that both some adherent corrosion products and the exposure of alloy layer were responsible for the drop in the rate of loss of weight with time.

As mentioned in an earlier paragraph, it was observed that the initial rate of loss of weight of the coating on the rings and wire was considerably higher than that for hot-dipped sheets. To investigate further the effect of size and shape of the sample on the rate of loss as determined by this accelerated corrosion test, zinc wires and rods of diameters ranging from 0.036 to 1.28 cm. were run on the rotating alternate immersion machine. The results are plotted in Fig. 9 and very definitely show a rapid slowing down in the rate of weight loss with increasing size of wire. A similar test is planned to be carried out in an outdoor exposure.

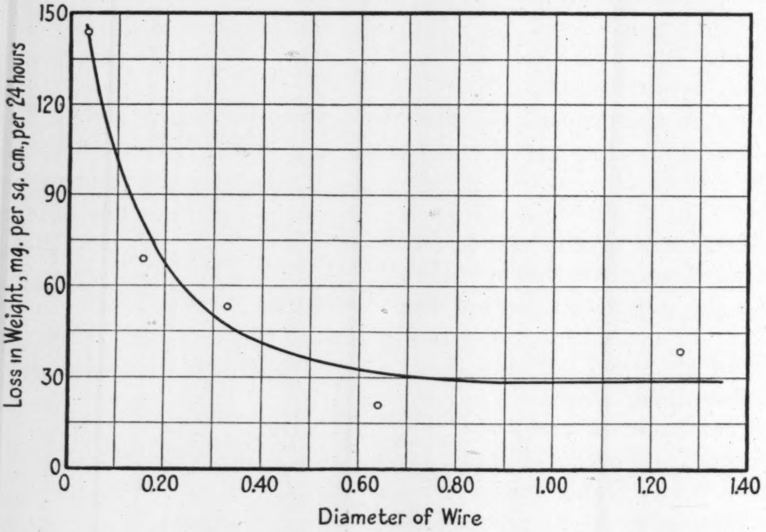

FIG. 9.—Showing Results of Tests on Wire on the Rotating Alternate Immersion Machine.

In comparing the controlled outdoor exposure test data thus far collected, with the earlier field observations and with the accelerated laboratory test data, it is important to note the fact that the apparent slowing down in rate observed in the accelerated test was not confirmed. This accelerated test cannot, therefore, be considered as a reliable means of judging the serviceability of hot-dipped coatings in an industrial atmosphere.

SUMMARY

In the outdoor exposure test in the industrial atmosphere of New York City comparing sherardized and hot-dipped coatings on small lengths of steel tubes, no differences were found in the rate of loss of weight between these coatings, or between the zinc and zinc alloy layers of hot-dipped coatings. The rate of loss of weight has been found to be approximately 3.5 mg. per sq. cm. per year.

In a second outdoor test, specimens exposed for a period of one year to the normal industrial atmosphere of New York City (the same as in the first test), the rates of loss of weight of the hot-dipped, heat-treated hot-dipped and sherardized coatings, as well as of two grades of rolled zinc sheet, were very nearly the same, approximating 2.5 mg. per sq. cm. per year. This value is somewhat less than that determined for similar coatings on short tubes. However, it seems likely that this difference may be reasonably attributed to the difference in size and shape of the specimens. Again, as in the first test, it is apparent that in this atmosphere the relatively pure zinc and the alloy layers of the coatings lose weight at a similar rate.

In the accelerated outdoor test using a water spray to simulate additional rainfall, the weathering rate of zinc coatings was doubled without materially affecting the relative individual performance of the different types of coating. The data indicate that the use of an outdoor spray for speeding up normal corrosion rates offers more promise of furnishing reliable information concerning zinc coatings than any laboratory accelerated test yet studied.

The laboratory accelerated test (rotating alternate immersion test), showed a slowing down with time in the rate of loss of weight of hot-dipped coatings, the most pronounced change in which was approximately coincident with the exposure of the alloy layer. As the exposure tests made in the industrial atmosphere of New York City show no appreciable difference in the rate of loss of weight of the relatively pure zinc and the alloy layers of a hot-dipped coating this accelerated test cannot be considered to have given a reliable picture of the performance of such coatings in this type of atmosphere.

The results of the rotating alternate immersion test did, however, indicate several interesting facts, the most significant being that the size and shape of the specimen may have a pronounced effect upon the rate of corrosion.

Our experience leads us to conclude that an accelerated laboratory test designed to determine reliably the suitability of a material for service in a particular locality should meet certain important requirements:

1. Similar films or layers of corrosion products should result as occur under actual service conditions;

2. The test should accelerate the corrosion of the various constituents of the material at the same relative rate as experienced in service; and

3. The corroding electrolyte should be such as to afford the electrochemical relationships of the different constituents as obtain in service.

DISCUSSION

MR. E. A. ANDERSON[1] (*presented in written form*).—The accurate data which the authors have presented on the outdoor corrosion of a related group of materials are in themselves of great interest and value. These data have an additional interest by virtue of the comparison which is given with an accelerated weathering test. Accelerated tests have been subjected to this type of scrutiny all too seldom.

We have found it particularly interesting to compare the authors' results with exposure tests made at Palmerton on an almost identical range of materials in an industrial atmosphere of slightly milder character and free from salt air. Attempts to correlate these outdoor tests with an accelerated test employing an atmosphere high in CO_2, SO_2 and moisture proved quite as unsuccessful as the similar attempt by the present authors reported in Tables I and II and Figs. 3 and 4.

The authors seem to us to have underestimated the influence of adjacent zinc coatings on the corrosion of exposed iron surfaces. On the immediate coast complete protection of exposed iron has been observed for a distance of as much as $\frac{1}{4}$ in. from the zinc coating. In addition to the complete protection afforded the bare iron immediately adjacent to the zinc, there is also an effect by the zinc on the character of the rust formed in the surrounding areas. The presence of zinc, probably as salts carried onto the iron surfaces, causes the formation of a distinctly more protective type of rust. This rust has more the appearance of a glaze than of the normal porous rust deposit.

In studying our own exposure tests on ordinary galvanized sheets in comparison with portions of the same sheet annealed to convert all of the zinc to zinc-iron alloy layer, we concluded that the equality of corrosion rates was more apparent than real. The specimens having an alloy coating showed an immediate gain in weight when first exposed. This gain in weight was accompanied by the formation of small rust areas which, at the end of six months' exposure, amounted to 25 per cent of the surface area. Simple calculation shows that if this 25 per cent of the sheet is assumed to gain weight at the same rate as an uncoated sheet, the balance of the sheet, that is the alloy coating, must lose weight at a distinctly higher rate than the specimens having normal zinc surfaces. Since the character of the rust must be altered by the intimate contact with the zinc-iron alloy surrounding it, this calculation can only be considered as qualitative.

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[1] Research Division, New Jersey Zinc Co., Palmerton, Pa.

We feel that the data in the paper, as well as our own results just described, show clearly that the corrosion of the zinc-iron alloy is certainly no slower than that of the outer zinc coating and that there is some evidence that it may be somewhat faster. In all events neither of the accelerated tests tried has yielded this result. It is of distinct importance in the development of accelerated tests that atmospheric exposure data of this sort be duplicated, at least qualitatively, by the proposed test.

MR. R. F. PASSANO.[1]—I think the authors have done an extremely valuable thing. The suitability of coatings exposed to the atmosphere is judged, in general, by the type of corrosion products which form on the surface. If the indications are as I have gathered them to be, namely, that iron-zinc layers corrode at the same rate as does zinc in the atmosphere, then, the appearance of the coating after a given length of time governs its usefulness rather than its loss of weight.

Until recent years, it has been accepted that zinc offered actual electrolytic protection to iron by virtue of its position in the electromotive series. On the racks of the Society's galvanized sheet test[2] zinc washers were used under the heads of the galvanized bolts which hold the sheets on the racks. At Key West zinc salts have definitely streamed down from the washers and discolored a portion of the adjacent iron mechanically. This effect cannot be generalized since it does not occur in many locations. The success of zinc as a protective coat lies in its ability to form an oxide-carbonate protection of it own rather than in its electromotive position.

There is offered in this paper the first piece of constructive evidence regarding th performance of galvanized sheets in the atmosphere and in accelerated tests. In both the "simulated atmospheric" test and the immersion test in ammonium chloride the rate of corrosion materially decreases when the iron-zinc layers are reached, whereas the rate of corrosion continues in the atmosphere. Laboratory tests are not, then, such faithful guides to prospective performance as are investigations made under service conditions.

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[1] Research Engineer, The American Rolling Mill Co., Middletown, Ohio.

[2] Report of Subcommittee VIII, Committee A-5, on Field Tests of Metallic Coatings, *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part I, p. 191 (1927).

DEVELOPMENT OF ZINC-BASE DIE-CASTING ALLOYS

BY D. L. COLWELL[1]

SYNOPSIS

Zinc-base die-casting alloys have been tremendously improved. The history of this improvement is illustrated in a series of charts, which show the effects of normal and accelerated aging on the size and physical properties of zinc-base die castings. Certain data from tests made by Subcommittee XV on Die-Cast Metals and Alloys of the Society's Committee B-2 on Non-Ferrous Metals and Alloys have been included.

The following conclusions are reached: Zinc-base die castings containing aluminum can now be used as an engineering material, as their physical properties and permanence have been enormously improved. Zinc-base die castings containing tin and very low aluminum are permanent. It is absolutely necessary to use zinc of the highest purity in the first class of alloys but not in the second. The water-vapor aging test is likely to lead to false conclusions. The paraffin aging test may prove more satisfacory.

INTRODUCTION

The die-casting process has been defined as the process of casting molten metal into permanent molds under comparatively high pressure. This definition does not include such operations as permanent mold casting, hot pressing, casting in plaster molds, etc., and therefore present processes of forming copper-base alloys are all excluded. The die-casting process at present is limited to metals and alloys whose melting point is about that of aluminum, 660° C. (1220° F.), or below; and includes alloys based on tin, lead, zinc and aluminum. The early development of the process depended on the tin and lead-base materials, and during the last few years the aluminum-base alloys have received the greater amount of attention. The zinc-base alloys, however, were responsible for the early growth of the industry, and today are die cast in greater tonnage than all other alloys combined. These zinc alloys have been improved immensely in the last few years; and the object of this paper is to record some of the facts of this improvement.

Pack**(9)**[2] estimates the die-casting production for 1929 at $40,000,000, and it is probably safe to say that over half of this production was in zinc-base alloys. A large proportion of these zinc-alloy castings was used by the automotive industry in such parts as speedometers, fuel pumps, carburetors, radiator caps, locks, windshield wipers, body hardware, etc., but the use of zinc die castings in other manufacturing is steadily increasing. Household utility machines are using even more zinc die castings than ever; and as their permanence and strength improve, so does their use in such parts as vending machines, motion picture projectors, radios, office appliances, building hardware, electrical appliances, and light manufacturing of all kinds. In Fig. 1 is illustrated an electrical wiring box and in Fig. 2 a motor frame, both of which are entirely satisfactory as zinc die castings and which would cost several times as much to manufacture by any other process. The economies possible through the use of modern zinc-base die castings are responsible for their application wherever suited, and the zinc alloys today are suited to parts that it would not have been safe to die cast in zinc five years ago.

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[1] Metallurgist, Stewart Die Casting Corp., Chicago, Ill.

[2] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended hereto.

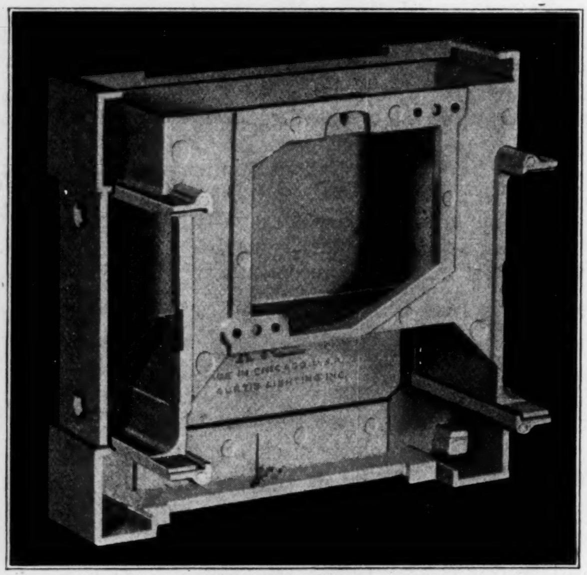


FIG. 1.—Electrical Wiring Box of Zinc-Base Alloy.

HISTORICAL

The first die casting with a zinc alloy was a natural outgrowth of the tin and lead compositions used at the beginning, such as "Parsons White Brass." Campbell(1) gives the composition of this as 5 per cent copper, 30 per cent zinc, and 65 per cent tin. This gradually developed into a composition similar to alloy No. XVIII as tested by Subcommittee XV on Die-Cast Metals and Alloys of the Society's Committee B2 on Non-Ferrous Metals and Alloys (hereafter referred to as the committee), containing 3 per cent copper, 6 per cent tin, 0.5 per cent aluminum and 90.5 per cent zinc(2). This composition is

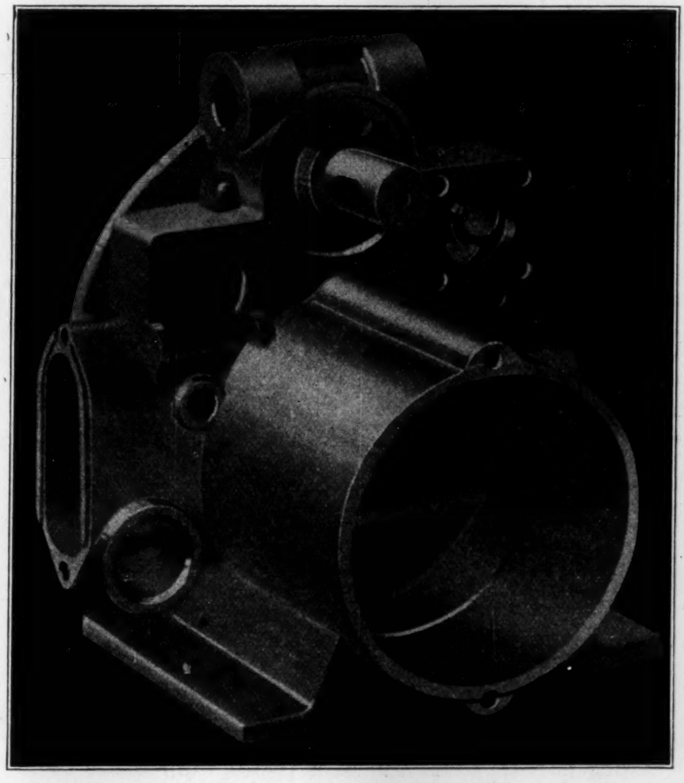


FIG. 2.—Motor Frame and Assembly Base of Zinc-Base Alloy.

still used to a certain extent and, as will be shown later, is not entirely without merit.

The next development was the one which led to unfortunate experiences with die castings; and the results of these experiences are still uppermost in the minds of many engineers. It was discovered that a zinc-base alloy containing from 1 to 5 per cent copper and from 1 to 20 per cent aluminum was much more easily cast than the alloy containing tin, and also had physical properties which were double those of the older compositions. Quantities of castings made of these alloys containing aluminum went into service, and the resulting failures are still remembered by many when die castings are considered. Even die castings made of tin-base and aluminum-base materials, which are absolutely permanent, suffered in reputation because of the premature failure of this one series of zinc-base alloys. This point has been well covered by Rosenhain(3), who points out that it has been necessary "to counteract in so far as possible the damaging effects of such statements upon the reputation of perfectly satisfactory and reliable materials." One of these failures is illustrated in Fig. 3, which is a reproduction of a photograph made in 1930 of a casting made in 1914. This casting contained both tin and high aluminum, and that combination in a zinc alloy is fatal.

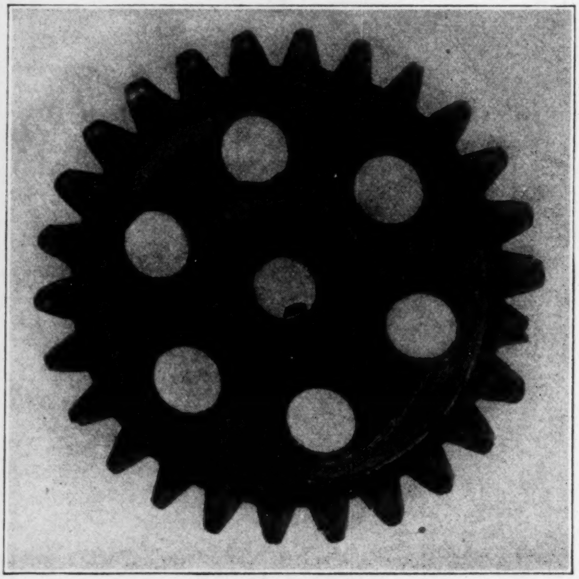


FIG. 3.—Die-Cast Gear Made in 1914 and Photographed in 1930.

Analysis: Copper 3.6 per cent, tin 6.2 per cent, aluminum 7.0 per cent, balance high-grade zinc.

A quantitative determination of the expansion of an alloy containing aluminum and lead is shown in Fig. 4. Several dimensions of a valve tappett guide have been accurately measured at intervals over a seven-year period. This casting was made in 1921 of Prime Western zinc and kept on a dry shelf in Chicago. It has cracked open in several places, but does not look nearly as bad as the gear in Fig. 3. If this casting had been stored in a moist tropical climate, its disintegration would have been much more rapid.

A metallurgical study of these zinc alloys containing aluminum was made by Rosenhain, Haughton and Bingham in 1920(4), by Hanson and Gayler in 1922(5), and by Brauer and Peirce in 1922(6). The latter paper brought out the following facts about zinc alloys containing aluminum which are generally accepted among zinc-alloy people today:

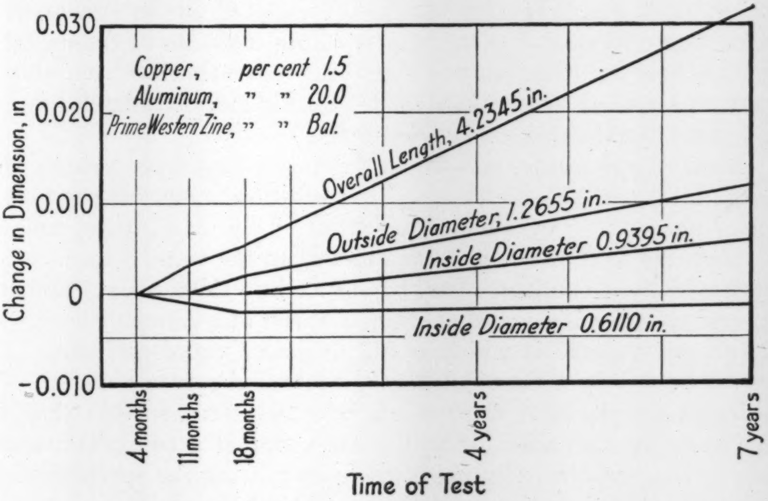


FIG. 4.—Expansion of Poor Zinc-Base Alloy Over Seven-Year Period.
Tests made on valve tappett guide No. B275.

1. The failure illustrated in Fig. 3 and the swelling plotted in Fig. 4 are due to intercrystalline oxidation.
2. The decomposition of the unstable beta constituent into alpha plus gamma multiplies the amount of intercrystalline oxidation.
3. The action is accelerated by lead, and perhaps by cadmium.
4. The action is accelerated by tin.
5. The action is retarded by copper and perhaps by nickel.
6. The use of high purity zinc in making these alloys is essential.

TESTS

The publication of the paper of Brauer and Peirce started an immense amount of work on the improvement of zinc-base die-casting alloys, and began what might be termed the "modern period" in the history. The water-vapor test which they used has met with general approval as an accelerated method of measuring the life of zinc alloys, although it has certain limitations which will be discussed later. Early water-vapor tests were made at 95° C. (200° F.) and others were made at 70° C. (160° F.). Both of these temperatures are used by laboratories cooperating in the committee's testing. A paraffin bath at these temperatures has also been used in an endeavor to separate deterioration due to oxidation from that due to the unstable beta constituent. Oxidation in the water-vapor test has been unduly severe and has led to a certain amount of difficulty in correlating the accelerated tests with normal aging tests.

Tests of specimens reported in this paper have been made either on standard A.S.T.M. die-cast test bars(7) or on actual die castings of various shapes. They have been supported by laying their ends on zinc supports so that all sides are exposed to the water vapor; or, in the case of the committee tests, by suspending them above the bath. The test chamber is a vessel containing water at a constant level with a large space above it which is full of water vapor and air. The water is heated by a thermostatically controlled source of heat. The specimens are placed in the space above the water, so that they are in constant contact with air and water vapor at a constant temperature. The paraffin bath test is made by placing the specimens in a vessel of paraffin in a thermostatically controlled oven.

In several cases normal aging tests have been performed by storing specimens in a cabinet and measuring or testing them at intervals. The committee's accelerated tests are being checked by normal outdoor aging tests in six different climatic locations, and by normal indoor aging tests in four additional locations(8). The results of these tests, however, are not yet available.

Deterioration of the specimens in aging tests was measured at first by increase in weight. Expansion of the samples was then tried as a more practical means of establishing the permanence of the alloys. Measurement of deterioration in physical properties, notably Charpy impact, tensile strength, and elongation in tension, is necessary in addition to expansivity measurements in order to establish the permanence of zinc-base die castings as engineering materials.

DATA

The data are presented in a series of figures which graphically illustrate the changes occurring in aging tests in concise form. Figures 10, 11 and 12 were plotted from results of committee tests, although they are not intended to present all the facts on zinc alloys accumulated by them. Three laboratories conducted accelerated tests for the committee on specimens from six producers. Only one of the three, however, paralleled the water-vapor test with a paraffin test, and so results from that laboratory only are used here. The results from the other laboratories, however, are closely parallel to these. The alloys picked are only those in general use at the present time. Alloys Nos. XIII, XVII, XIX and XX(2) are omitted from this study because they represent particular alloys of one producer, but will be included in later presentations of committee data. Also

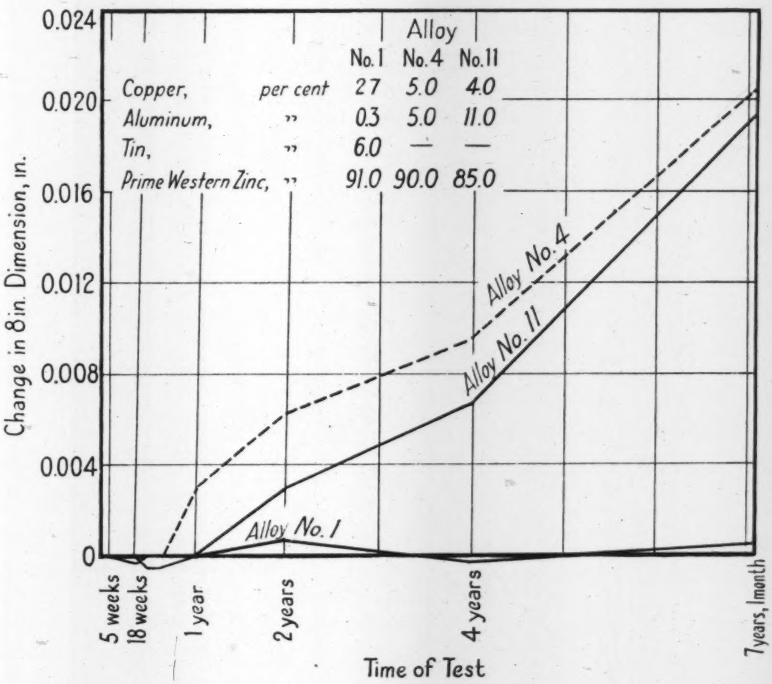
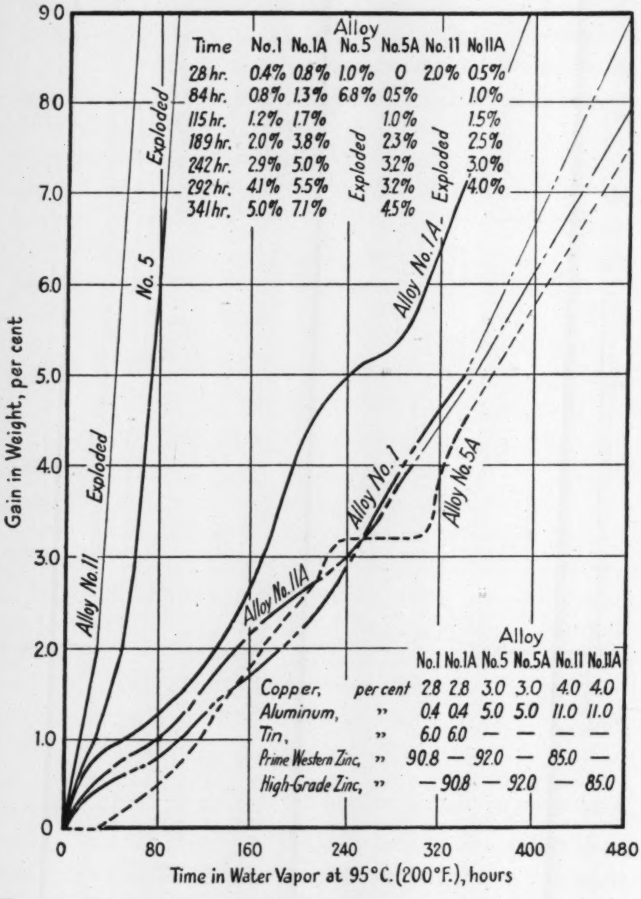


FIG. 5.—Comparison of Actual Expansion of Various Alloys Made with Prime Western Zinc over Seven-Year Period.

only three of the six producers were included in the averages because only these three submitted complete sets of specimens of the five alloys, Nos. XIV, XV, XVI, XVIII and XXI, for this test. The results for alloys Nos. XV and XVI are so very nearly the same that the two are averaged together in these curves. It is admitted that this is contrary to the intention of the committee in submitting the two alloys, as a comparison was desired between alloys Nos. XV, XVI and XXI. These three are all of the same nominal composition, but based on three different grades of zinc. A further comparison of Nos. XV, XVI and XXI will be made in later committee studies.

Each point on each curve represents the average from fifteen or more specimens. Modern statistical analysis might show more accurate comparisons, but it is believed that the conclusions presented here are valid, and that the qualitative comparisons of alloys are accurate.



Time	Alloy No. 1	No. 1A	No. 5	No. 5A	No. 11	No. 11A
28 hr.	0.4%	0.8%	1.0%	0	2.0%	0.5%
84 hr.	0.8%	1.3%	6.8%	0.5%		1.0%
115 hr.	1.2%	1.7%		1.0%		1.5%
189 hr.	2.0%	3.8%		2.3%		2.5%
242 hr.	2.9%	5.0%		3.2%		3.0%
292 hr.	4.1%	5.5%		3.2%		4.0%
341 hr.	5.0%	7.1%		4.5%		

		Alloy No. 1	No. 1A	No. 5	No. 5A	No. 11	No. 11A
Copper,	per cent	2.8	2.8	3.0	3.0	4.0	4.0
Aluminum,	"	0.4	0.4	5.0	5.0	11.0	11.0
Tin,	"	6.0	6.0	—	—	—	—
Prime Western Zinc,	"	90.8	—	92.0	—	85.0	—
High-Grade Zinc,	"	—	90.8	—	92.0	—	85.0

FIG. 6.—Improvement in Aluminum-Containing Alloys due to use of High-Grade Zinc.

PERMANENCE OF ALLOY CONTAINING TIN

The expansion with normal aging shown in Fig. 4 represents about the worst that can happen in temperate climates. The greatest dimensional change is in the overall length of 4.2345 in., and amounts to 0.031 in. increase in an overall length of $4\frac{1}{4}$ in. in seven years. The alloy is one which was not sold commercially by the larger manufacturers at any time, as it was one of the worst of its type. It contained very high aluminum and was made with Prime Western zinc, so that it contained over 1 per cent lead.

A second illustration of expansion in normal aging is shown in Fig. 5. These die-cast bars were $\frac{3}{4}$ in. square and 8 in. long, and were all made of alloys based on Prime Western zinc. The alloys containing aluminum (Nos. 4 and 11), were stable for about one year, and then grew rapidly. The alloy containing tin, similar to alloy No. XVIII of the committee, has not changed in size at all in over seven years. The variations of the curve from the base line are less than 0.001 in., and can be considered experimental variations. It is interesting to note that alloy No. 4 was considered for specification by the Non-Ferrous Metals Section of the Society of Automotive Engineers Standards Committee in 1920. It was never adopted, however.

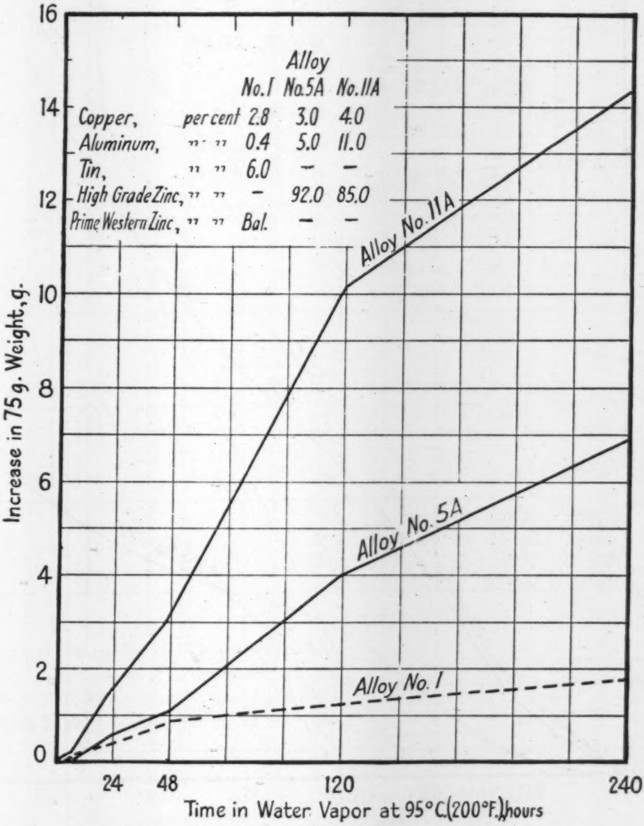


FIG. 7.—Comparison of Three Alloys Used in 1923.

That the permanence in ordinary climates of a zinc-base alloy containing tin and very low aluminum as shown by Fig. 5 is not an accident is shown by measurements made on a die-cast switch lever of that composition. This lever, No. 23853, was cast in 1913 from an alloy made of Prime Western zinc and containing 3.2 per cent copper, 6.9 per cent tin, and 0.3 per cent aluminum. In 1930, seventeen years later, it was measured again with the following results:

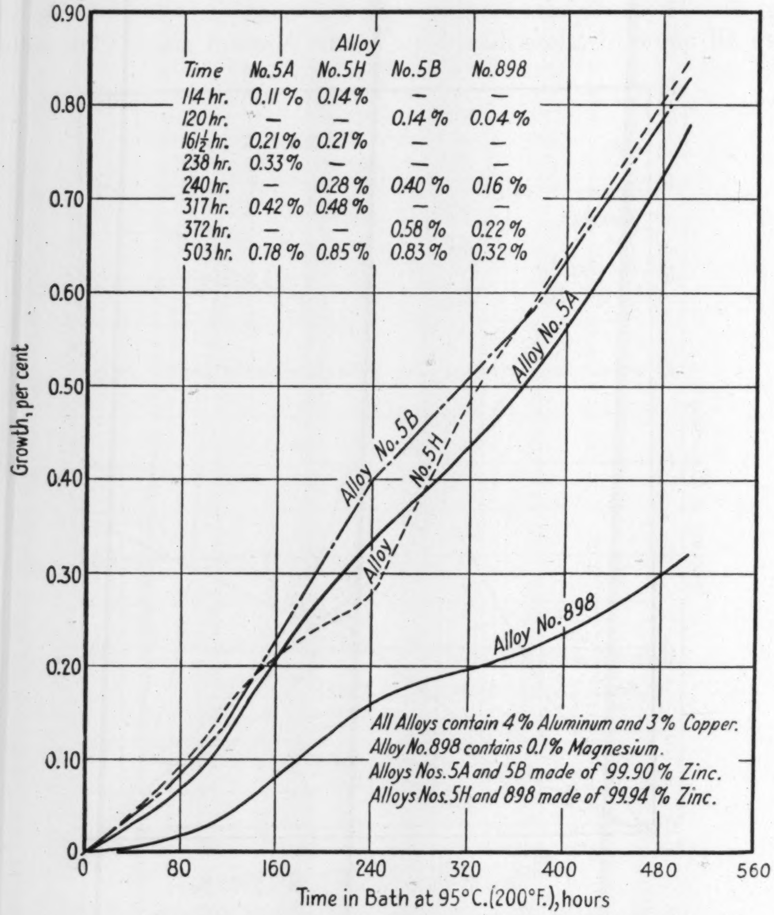
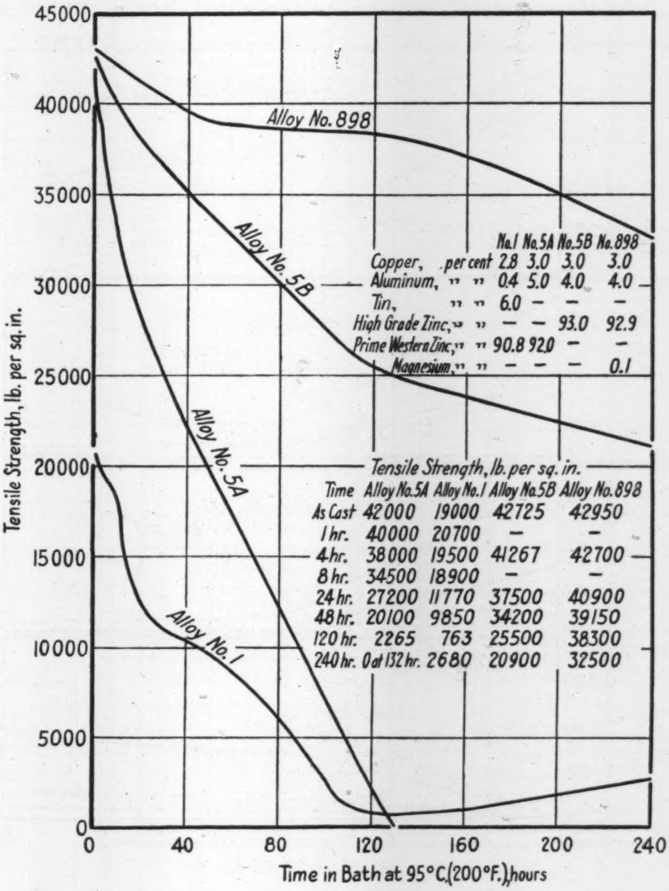


FIG. 8.—Relative Expansions of Alloys With and Without Magnesium. Addition of 0.1 per cent magnesium improves alloy.

1913 MEASUREMENT	1930 MEASUREMENT	CHANGE
0.472 in.	0.470 in.	−0.002 in.
0.204 "	0.205 "	+0.001 "
0.220 "	0.220 "	No change

Inasmuch as errors in measurement due to the personal factor, to dirt and oxides, and to differences in temperature, over a seventeen year period might be considerable, the casting can be considered permanent.



		No. 1	No. 5A	No. 5B	No. 898
Copper,	per cent	2.8	3.0	3.0	3.0
Aluminum,	" "	0.4	5.0	4.0	4.0
Tin,	" "	6.0	–	–	–
High Grade Zinc,	" "	–	–	93.0	92.9
Prime Western Zinc,	" "	90.8	92.0	–	–
Magnesium,	" "	–	–	–	0.1

Tensile Strength, lb. per sq. in.

Time	Alloy No. 5A	Alloy No. 1	Alloy No. 5B	Alloy No. 898
As Cast	42000	19000	42725	42950
1 hr.	40000	20700	–	–
4 hr.	38000	19500	41267	42700
8 hr.	34500	18900	–	–
24 hr.	27200	11770	37500	40900
48 hr.	20100	9850	34200	39150
120 hr.	2265	763	25500	38300
240 hr.	0 at 132 hr.	2680	20900	32500

FIG. 9.—Comparison of Tensile Strengths With and Without Magnesium.

USE OF HIGH-GRADE ZINC

The use of high-grade zinc analyzing 99.90 per cent minimum zinc content brought an improvement in the zinc-aluminum alloys illustrated in Fig. 6. This test was one of the early tests where deterioration was measured by increase in weight, and the increase in weight of all alloys due to surface oxidation and carbonate formation obscures the results. Brauer and Peirce(6) show data on this point that are more conclusive. One point worthy of note, however, is that the tin alloy is apparently not improved by the use of high-grade zinc.

A comparison of the three best alloys as shown by Fig. 6 was made in Fig. 7. Here, too, deterioration was measured by increase in weight, and consequently is quantitatively inaccurate; but as a result of this test and the preceding one, the Stewart Die Casting Corp. standardized on alloys Nos. 1 and 5A, using No. 1 for permanence and No. 5A for strength. Alloy No. 5A is made of high-grade zinc, and No. 1 of Prime Western zinc.

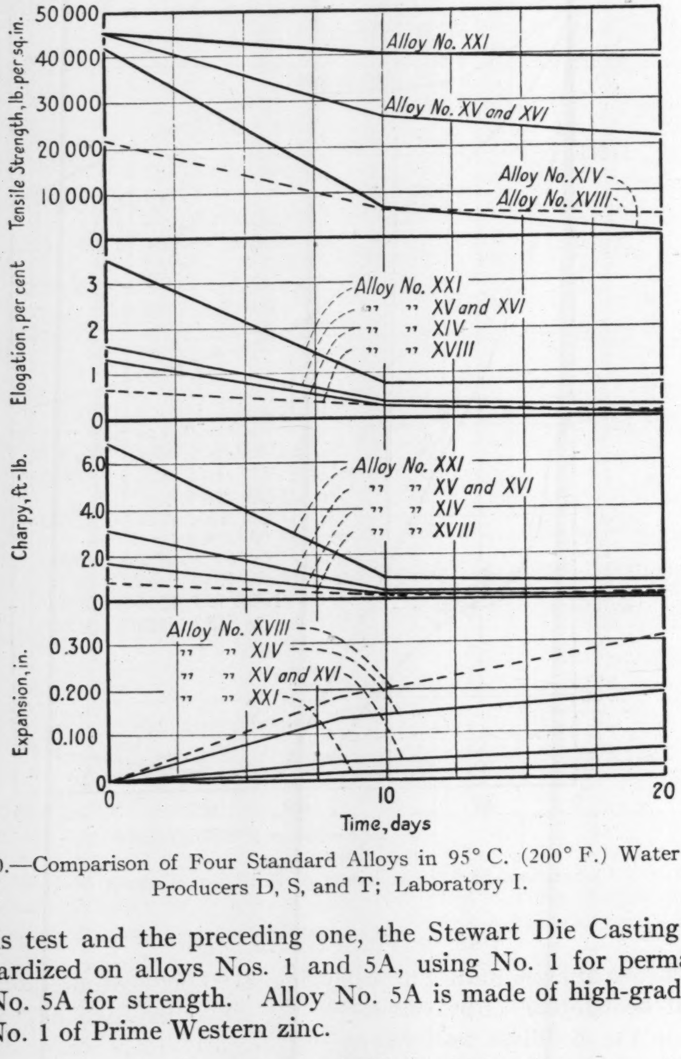


FIG. 10.—Comparison of Four Standard Alloys in 95° C. (200° F.) Water Vapor; Producers D, S, and T; Laboratory I.

ADDITION OF MAGNESIUM

The addition of magnesium made a further improvement in the permanence of alloy No. 5 in the 95° C. (200° F.) water-vapor test.

The relative expansion of the same alloy made with and without the addition of magnesium is shown in Fig. 8. The absence of any improvement due to the use of 99.94-per-cent zinc in No. 5H shows the better qualities of No. 898 to be due to the magnesium. Alloy No. 898 is also more permanent in its strength, as is shown in Fig. 9. A low-grade zinc alloy is shown here for comparison, and the low strength of No. 1 is worthy of note.

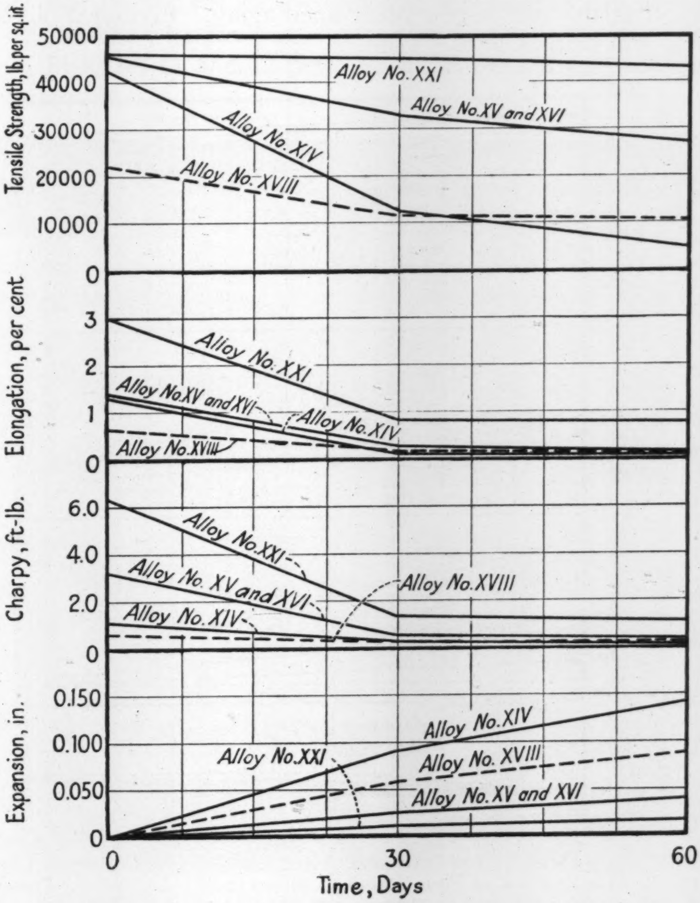


FIG. 11.—Comparison of Four Standard Alloys in 70° C. (160° F.) Water Vapor; Producers D, S, and T; Laboratory I.

The addition of magnesium to the 4 per cent aluminum 3 per cent copper alloy has an equally beneficial effect on the tensile strength and elongation with normal aging. A two-year-old casting was found to have the same strength and elongation as a new casting when it contained magnesium. The elongation is initially lower, but does not fall, while the tensile strength is permanent. Both the strength and elongation of the alloy without magnesium show over 50 per cent reduction at the end of two years' shelf aging. Five-year-old bars in this test will be broken this year.

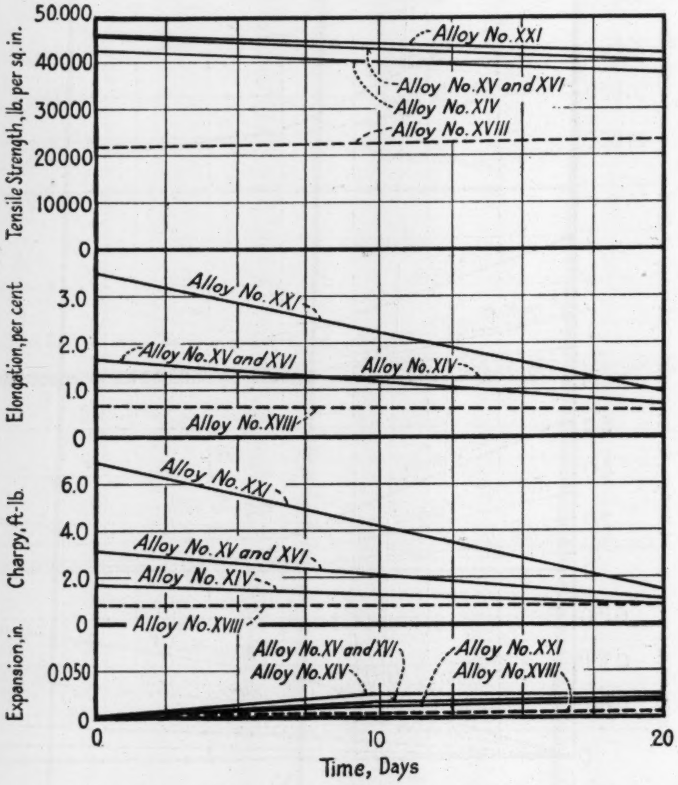


FIG. 12.—Comparison of Four Standard Alloys in 95° C. (200° F.) Paraffin; Producers D, S, and T; Laboratory I.

TESTS UNDER JURISDICTION OF SUBCOMMITTEE XV

In 1927, when the committee first drew up its list of alloys, the zinc-base die-casting alloys in use were of three general types. There was the alloy containing tin and low aluminum, shown as No. 1 in preceding curves and listed by the committee as No. XVIII. There was the No. 5 alloy, made with high-grade zinc and containing about 4 per cent aluminum and 3 per cent copper, and listed by the committee as No. XIV. This same alloy containing 0.1 per cent magnesium was listed by the committee as Nos. XV and XVI, depending on the brand of zinc used. Late in 1927, however, a new grade of zinc appeared on the market, made by a new electrolytic process, and containing about 99.99 per cent minimum zinc. The same magnesium-containing alloy made of this zinc was therefore added to the committee's list as No. XXI, and tested with the rest. A comparison of these four alloys is made in Figs. 10, 11 and 12 from A.S.T.M. data from Laboratory I as averaged for specimens of producers D, S, and T.

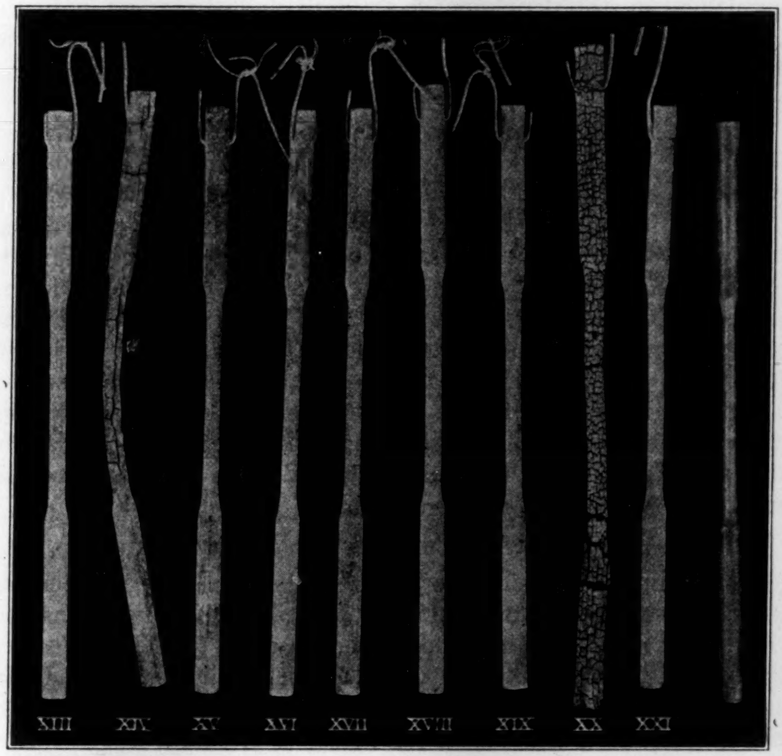


FIG. 13.—Round Test Bars After 20 Days in 95° C. (200° F.) Water-Vapor Test; Producer D; Laboratory B.

Several interesting and important facts are brought out in these curves. The tensile strength of No. XXI is almost permanent in all three tests. The tensile strength of No. XIV has the greatest drop. If oxidation is eliminated, as in Fig. 12, all alloys have practically constant tensile strengths.

Alloy No. XXI also shows the least expansion in both water-vapor tests. Alloy No. XVIII is worst in the 95° C. (200° F.) water vapor, but best in the 95° C. (200° F.) paraffin. Alloy No. XIV has the greatest expansion in all tests except for alloy No. XVIII in the 95° C. (200° F.) water vapor.

The elongation and Charpy curves are almost identical, and the two water-vapor tests give the same results in these two properties. Alloy No. 21 still is superior to the others, although it does suffer a very serious loss in ductility. Alloys Nos. XIV and XVIII are not relatively as bad in the paraffin aging as in either water-vapor test.

The 95° C. (200° F.) paraffin test indicates that alloy No. XVIII is permanent in size, permanent in strength, and permanent in ductility under the effect of heat without moisture. On this alloy, at least, the paraffin aging is more nearly representative of the normal aging shown in Fig. 5.

The deterioration in water vapor plotted in Fig. 10 is illustrated in Fig. 13. These round test bars were photographed after 20 days in water vapor at 95° C. (200° F.). The bar at the right is an untested bar. The photographic evidence of the relative deterioration in the water-vapor test is similar for bars from the other producers. Alloy No. XX represents the same sort of failure as was shown in the gear in Fig. 3. Improvement was effected in alloy No. XIV by the use of high-grade zinc, and in alloys Nos. XV and XVI by the use of magnesium. Alloy No. XXI is the final step in this test, obtained by the use of 99.99-per-cent zinc. Alloy No. XVIII looks bad after the water-vapor test, but accelerated aging without excessive oxidation, and normal aging, both show alloy No. XVIII to be satisfactory in permanence.

COMPARISON OF ACCELERATED AND NORMAL AGING

No definite relationship can be assigned at this time between life in the accelerated tests and life in service. It may develop that no correlation is possible for the following reasons: (1) The difference between the effect of the water vapor on the tensile strength and on the impact strength shows that the effect of the accelerated test varies with the property measured; (2) life in service is also variable, not only between different climates, but between different degrees of exposure in the same climate.

SUMMARY AND CONCLUSIONS

Referring to the improvements in the zinc-base alloys, as traced historically in this paper, A.S.T.M. alloy No. XX represents the alloy in use in 1918; alloy No. XIV in 1922; alloys Nos. XV and XVI in 1925; and alloy No. XXI in 1929. Alloy No. XVIII was used in 1913, but is also used in 1930. Its relative value is not fairly shown by the water-vapor test, because of undue oxidation.

Work is now in progress on zinc-base alloys that are even more permanent than alloys Nos. XVIII and XXI. This paper was up to date in 1929, but 1930 offers further improvements, as alloys are now available that are superior to the best of 1929. Undoubtedly, a few years more will see still greater improvements, and zinc-base alloys may soon be as free from "aging troubles" as stainless steel is from rusting troubles.

The following conclusions are believed justified from the data submitted:

1. The zinc-base die-casting alloys containing aluminum have been tremendously improved during the last few years. Their physical properties and their permanence are now satisfactory for use as engineering materials.
2. These alloys owe their improvement to the use of zinc of higher and higher purity and to the use of magnesium.
3. The zinc-base die-casting alloys containing tin and very low aluminum are permanent in size and shape, although their physical properties are comparatively low.
4. The water-vapor test emphasizes the oxidation too strongly, particularly at 95° C. (200° F.). The 70° C. (160° F.) test is to be preferred for the alloys containing aluminum.
5. Aging in paraffin at 70° C. (160° F.) or at 95° C. (200° F.), in connection with a Charpy impact test, appears to be a preferable method of accelerated testing of die castings.

REFERENCES

(1) William Campbell, "A List of Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part I, p. 213 (1922).

(2) For list of die-casting alloys, see report of Committee B-2, *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 193 (1929).

(3) Walter Rosenhain, "Some Cases of Failure in 'Aluminium' Alloys," *Journal*, Inst. Metals (British), Vol. XXVII, No. 1, p. 219 (1922).

(4) W. Rosenhain, J. L. Haughton, K. E. Bingham, "Zinc Alloys with Aluminium and Copper," *Journal*, Inst. Metals (British), Vol. XXIII, No. 1, p. 261 (1920).

(5) D. Hanson and M. L. V. Gayler, "A Further Study of the Alloys of Aluminium and Zinc," *Journal*, Inst. Metals (British), Vol. XXVII, No. 1, p. 267 (1922).

(6) H. E. Brauer and W. M. Peirce, "The Effect of Impurities on the Oxidation and Swelling of Zinc Aluminum Alloys," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 68, p. 796 (1923).

(7) See report of Committee B-2, *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part I, p. 203 (1928).

(8) See report of Committee B-2, *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 198 (1929).

(9) Charles Pack, "Advances in Die-Cast Metals for Automotive Use," Symposium on Developments in Automotive Materials, Detroit Regional Meeting, Am. Soc. Testing Mats., March 19, 1930.

DISCUSSION

Mr. F. J. Tobias[1] (*by letter*).—The author emphasizes two points which I believe are not proved to the extent that they could be taken as definite conclusions. First, the statement that zinc-base die castings containing tin and very low aluminum are permanent as compared with castings which are made of an alloy of a chemical composition of 3 per cent copper, 4 per cent aluminum, 0.10 per cent magnesium, balance of the highest grade zinc of a purity of 99.99 per cent plus, and second, that a zinc-base alloy containing tin is apparently not improved by the use of high-grade zinc. These statements seem to be somewhat contradicted by the extensive tests of the Society's Committee on Die-Cast Metals and Alloys. In these tests, which are also mentioned in Mr. Colwell's paper, results have been obtained which show that alloy No. XXI with a chemical composition of 3 per cent copper, 4 per cent aluminum, 0.10 per cent magnesium, balance of the highest grade zinc of a purity of 99.99 per cent plus, has shown in linear expansion on the $\frac{3}{4}$-in. section of the flat tension test bar the following:

After 10 days' exposure to 95° C. water vapor	0.0011 in.
" 20 " " " 95° C. " "	0.0019 in.
" 60 " " " 70° C. " "	0.0011 in.
" 90 " " " 70° C. " "	0.0032 in.

These data have been taken from tests of the New Jersey Zinc Co. Laboratories at Palmerton on specimens of the Newton Die Casting Corporation.

On alloy No. XVIII of a chemical composition of 3 per cent copper, $\frac{1}{2}$ per cent aluminum, 6 per cent tin, balance Prime western zinc the linear expansion on the same producers' test bars are as follows:

After 10 days' exposure at 95° C. water vapor	0.0101 in.
" 20 " " " 95° C. " "	0.0354 in.
" 60 " " " 70° C. " "	0.0114 in.
" 90 " " " 70° C. " "	0.0163 in.

In making these test bars out of the same chamical formula but using instead of Prime Western a zinc of the purity of 99.94 per cent (the purest commercial zinc available at the time the alloy was made) the linear expansion on the same test bar of alloy No. XVIII-B showed the following:

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[1] Research Engineer, The Newton Die Casting Corp., New Haven, Conn.

After 10 days' exposure at 95° C. water vapor	0.0049 in.
" 20 " " " 95° C. " "	0.0181 in.
" 60 " " " 70° C. " "	0.0073 in.
" 90 " " " 70° C. " "	0.0084 in.

All previous mentioned data have been gathered by the same laboratory, using the same apparatus and procedure for the different alloys. These tests have also been duplicated by the American Brass Co. in Waterbury, Conn., and their findings are as follows:

Expansion tests were made on the flat test bar, the values given being the total expansion in inches measured over the full length of the specimen. The second set of values shows the expansion reduced to ¾ in. length to make it possible to compare the data between the two testing laboratories.

ALLOY NO. XXI

	TOTAL EXPANSION, IN.	EXPANSION, AVERAGE, ¾ IN.
After 10 days' exposure at 95° C. water vapor	0.020	0.00166
" 20 " " " 95° C. " "	0.035	0.00296
" 30 " " " 70° C. " "	0.013	0.00108
" 60 " " " 70° C. " "	0.021	0.00175

ALLOY NO. XVIII

After 10 days' exposure at 95° C. water vapor	0.202	0.01683
" 20 " " " 95° C. " "	0.361	0.0300
" 30 " " " 70° C. " "	0.080	0.0066
" 60 " " " 70° C. " "	0.119	0.0099

Unfortunately this laboratory has not made tests on alloy No. XVIII-B which contains the high-grade zinc.

The American Brass Co. also made paraffin tests at 95° C., at 10 days and 20 days. These tests represent ideal conditions in excluding every possibility of water vapor and oxidation; however, this is a condition which very seldom exists where die castings are used. My belief is that data from these paraffin tests are not complete enough at the present time to make it possible to use them for purposes of comparison.

I agree with Mr. Colwell in his statement that the oxidation in the water-vapor test has been unduly severe and has led to a certain amount of difficulty in correlating the accelerated test with normal aging tests. In addition I may mention that, so far as I know, up to the present time in water-vapor tests the water used has not been taken into consideration in regard to the chemical analysis and it would be worth while in the future to have this in mind.

It is a fact that the soldering qualities of a zinc-base alloy containing tin are better than those of a zinc-base alloy without tin. The machining qualities are also more favorable in a zinc-base alloy containing tin. These advantages, however, are minimized when taking into consideration the fact that the physical properties of a zinc-base die-casting alloy without tin are considerably higher. For example, alloy No. XVIII shows a tensile strength on a flat test bar specimen of 24,000 lb. per sq. in. Alloy No. XXI has a tensile strength of 48,500 lb. per sq. in. In approximately the same proportion is the elongation in favor of alloy No. XXI, and the Charpy impact value of alloy No. XVIII is 1.7 ft-lb. compared with 8.2 ft-lb. on alloy No. XXI.

Another disadvantage in using the zinc-base alloy containing tin is that the price of the alloy is increased owing to the use of tin.

The greatest drawback, however, in using an alloy of this type is the danger that contamination may occur in mixing up gates, overflows, reject castings, etc., of one alloy with the other as the smallest amount of tin in an alloy of the composition of No. XXI is detrimental to the alloy. To hold these two zinc-base alloys separate in a plant is one of the great problems which is best solved by eliminating one of the alloys. Our experience in the past is in favor of a zinc-base alloy without tin.

MR. D. L. COLWELL[1] (*author's closure by letter*).—Mr. Tobias compares alloy No. XVIII with No. XXI and advocates the use of alloy No. XXI only. He lists three disadvantages of alloy No. XVIII. I find myself in absolute agreement with him.

It is true that the water-vapor aging tests used by the committee indicate that alloy No. XVIII is not permanent in dimension. I have illustrated Mr. Tobias' figures in Figs. 10 and 11. Normal aging, however, in an ordinary climate, indicates that alloy No. XVIII is permanent in size and shape, as illustrated in a 7-year test in Fig. 5, and in the 17-year old switch lever measurements on page 482. Therefore, the water vapor test is not an accurate one for comparing the normal permanence of the two alloys. In my opinion, the paraffin aging test gives results more nearly comparable to normal aging in ordinary climates.

Mr. Tobias brings up an interesting point in mentioning the effect of the chemical analysis of the water used in the water-vapor test on the aging of the test bars. It is known that certain impurities have a tendency to pit the surface of the bars, and thus lower the apparent physical properties and accelerate the aging. This is another disadvantage of the water-vapor test.

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[1] **Metallurgist,** Stewart Die Casting Corp., Chicago, Ill.

SILVER SOLDERS

BY R. H. LEACH[1]

SYNOPSIS

This paper discusses the properties of alloys commonly called silver solders. The characteristics of silver solders are described and comparisons are made with other solders. The composition of fluxes and methods of using them are given. The proper procedure in making joints with silver solders is explained and suggestions offered regarding the grade of solder most suitable for use with different metals and alloys. The results of extensive research and practical experience in the use of silver solders is summarized with the purpose of presenting to those interested in joining metals, sufficient information to allow them to decide whether silver solders would be the best brazing alloy for any particular case.

INTRODUCTION

There are two general types of solders: soft solders and hard solders. The term soft solder is usually applied to compositions of tin and lead melting at temperatures between 400 and 500°F. These solders are used on both ferrous and non-ferrous metals and because of their low melting points, require a relatively small amount of heat —in many instances, the work is done with soldering irons. They have low tensile strength and although many of them are malleable and ductile, joints made with them will not stand heavy stresses.

The hard solders include the common spelter or brazing solders and other alloys of base metals which require at least a red heat to melt them. Spelter solders contain approximately equal amounts of copper and zinc and are brittle alloys. On account of this brittleness they are supplied in granular form. Other types of brazing solders which can be fabricated have lower percentages of zinc, but require correspondingly higher temperatures when used. Their flow points range as a rule above 1600°F. These solders give strong joints, but in many cases they are not sufficiently ductile to withstand heavy bending stresses and shock. Moreover the high temperatures required for their use is likely to cause damage to the metals or alloys which it is desired to join.

Silver solders should be classed as hard solders. The addition of silver to copper-zinc alloys lowers the flow point and a series of ternary alloys can be made which will flow freely at temperatures ranging from 1250 to 1600°F. These alloys have high tensile strength, are malleable and ductile, and can be rolled into thin sheets or drawn into fine wire. It is apparent that the flow points of silver solders are considerably below that of the ordinary base-metal brazing alloys, but strong joints can be made which will resist severe stresses and shock.

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[1] **Manager of Research and Development, Handy & Harman, Bridgeport, Conn.**

Although the alloys containing higher percentages of silver are primarily intended for use by the silversmithing industry, they are also used extensively by other industries. The alloys containing lesser amounts of silver are used for joining ferrous and non-ferrous metals where strong joints are required and where the temperatures necessary for the use of base-metal brazing solders are likely to damage the metal or alloys.

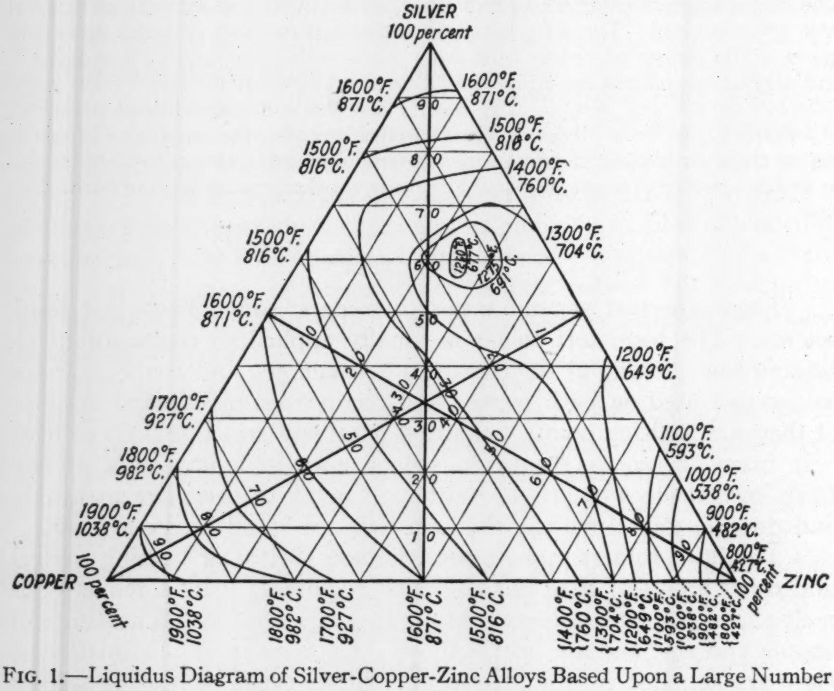
SILVER
100 percent
COPPER
100 percent
ZINC
100 percent
1600°F. 871°C.
1500°F. 816°C.
1400°F. 760°C.
1300°F. 704°C.
1200°F. 649°C.
1100°F. 593°C.
1000°F. 538°C.
900°F. 482°C.
800°F. 427°C.
1700°F. 927°C.
1800°F. 982°C.
1900°F. 1038°C.
1250°F. 677°C.
1275°F. 691°C.
10
20
30
40
50
60
70
80
90

FIG. 1.—Liquidus Diagram of Silver-Copper-Zinc Alloys Based Upon a Large Number of Cooling Curves Made in the Research Laboratory of Handy & Harman.

The use of silver solders has expanded rapidly during the past few years and there has arisen the necessity for some definite information regarding their characteristics. An examination of the literature shows very few data, consisting largely of formulas which in many cases specify a certain proportion of silver and brass. This is to be expected, because it is probable that many silver solders were made by adding silver to scrap brass, or possibly in some cases to a brazing solder in order to obtain a more malleable and lower melting alloy. The lack of any definite information regarding the physical properties of silver solders has tended to multiply the number of compositions in use. These compositions often show small variations in the percentages of the different metals; but with no definite knowledge available as to the effect of changing these percentages, it is natural that engineers hesitate to accept a change in composition even though it might be as small as 1 or 2 per cent difference in zinc, or the omission of 0.75 to 1 per cent of tin or some similar variation. The increasing use of silver solders resulted in the appointment of a subcommittee of the Society's Committee B-2 on Non-Ferrous Metals and Alloys to investigate silver and gold solders, and to recommend a suitable number of silver solder compositions to meet the different trade requirements. This committee completed its work and in June, 1928, submitted the Tentative Specification for Silver Solders (B 73 - 28 T) which were subsequently adopted as standard in 1929.[1] An appendix to these specifications gives a liquidus diagram of silver-copper-zinc alloys, reproduced as Fig. 1 of this paper, and the approximate melting, flow points and color of the different grades. The committee felt that further information would be desirable which has led to the preparation of this paper.

PHYSICAL PROPERTIES OF SILVER SOLDERS

The paper deals chiefly with ternary alloys of copper, silver and zinc, because investigations have shown that these alloys will meet most of the conditions where silver solders should be used. Special compositions may be justified in exceptional cases.

Melting Points:

The primary requisite of any solder or brazing alloy is that it should flow at a temperature below the melting points of metals or alloys to be joined and the liquidus diagram (Fig. 1) shows the flow points which can be obtained by varying the percentages of silver, copper and zinc.

The temperature at which the solder becomes liquid is commonly called the melting point. Some of the constituents in all of these alloys melt at lower temperatures than others and in this paper the term "melting point" refers to the solidus or temperature at which any part of the alloy starts to melt. The term "flow point" refers to the liquidus or the temperature at which the solder is entirely liquid. The flow point is usually the only one of particular interest, but when a second soldering operation is required, it is advisable to use a first solder which has a melting point above the flow point of the second solder. The difference in temperature between the melting point and the flow point will vary according to the composition of the alloy, and if the melting point is of vital importance it should be accurately determined for any particular composition.

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[1] 1929 Supplement to Book of A.S.T.M. Standards, p. 113.

An analysis of Fig. 1 shows that with a given ratio of copper and zinc the addition of silver lowers the flow point. In addition to this it will be seen that by using as much as 65 per cent of silver it is possible to produce a solder which will flow freely at approximately 1300°F. and at the same time contain only 15 per cent of zinc. Further increase of the percentage of zinc reduces the flow point to 1250°F.

TABLE I.—EFFECT OF CADMIUM ON THERMAL POINTS OF SILVER SOLDERS.

CHEMICAL COMPOSITION					
SILVER, PER CENT	COPPER, PER CENT	ZINC, PER CENT	CADMIUM, PER CENT	MELTING POINT, DEG. FAHR	FLOW POINT, DEG. FAHR.
65.0	20.0	15.0	....	1280	1325
65.0	20.0	12.5	2.5	1275	1325
65.0	20.0	9.0	6.0	1310	1345
65.0	20.0	5.0	10.0	1320	1370
65.0	20.0	....	15.0	1350	1385
20.0	45.0	35.0	....	1400	1510
20.0	45.0	30.0	5.0	1400	1485

Conversely those alloys containing lower amounts of silver will have correspondingly high flow points unless the zinc contents are abnormally high, in which case brittle alloys will result. It is evident, therefore, that malleable and ductile silver solders having low flow points must have relatively high percentages of silver.

For ordinary commercial uses, from 40 to 50 per cent of silver allows the proportions of zinc and copper to be held at about the same ratio as in common high brass and the flow point will be slightly above 1400°F.

With approximately this same silver content the percentage of zinc can be increased until it is equal to the copper and this will lower the flow point. There seems to be some prejudice, however, against the use of these higher zinc solders, although experiments have indicated that when proper care is taken, satisfactory joints can be made. The silver-copper eutectic which contains approximately 72 per cent of silver and 28 per cent of copper has a melting point which is approximately 1435°F.

Effect of Other Metals.—The addition of cadmium to high-zinc alloys makes their fabrication easier. The effect on the flow point of the substitution of cadmium for zinc depends upon the composition of the alloy. In alloys containing 65 per cent or more of silver the flow point is slightly raised, but in alloys containing relatively low percentages of silver the substitution of 4 to 5 per cent of cadmium lowers the flow point. Table I gives a few examples. It is also possible to produce malleable alloys of medium silver content with a higher percentage of combined cadmium and zinc than with zinc alone, thus giving slightly lower flow points.

The addition of tin in any appreciable amount lowers the flow point of the solder, but it also tends to make brittle alloys. Experiments have been conducted to determine whether there is any advantage in small percentages of tin and the results have not indicated that in the cases studied there is any specific advantage. If the simple ternary alloys will meet the trade requirements, it would seem to be unwise to use a fourth metal such as tin which makes a brittle alloy if sufficient amount of it is used to get any decided effect.

Nickel hardens the alloy and increases the flow point.

Lead and iron should not be present in any appreciable amount in silver solders as they serve no useful purpose and are likely to cause difficulties in working. The silver-lead eutectic which contains approximately 2½ per cent of silver and 97½ per cent of lead is sometimes used as a solder with the addition of a small amount of copper. This alloy has similar physical properties to those of soft solder and it should not be classed as a silver solder.

Malleability and Ductility:

Silver solders are malleable and ductile. These properties have an important bearing upon the character of silver-soldered joints because it is usual to find some of the original solder in the joint after the diffusion caused by heat of soldering is complete. It follows that joints made with these alloys will have greater resistance to bending stresses, shocks and vibrations than those made with brittle alloys. Another advantage of these properties is the ease with which the alloys can be fabricated into the form and size most suitable for their convenient and economical use.

Regardless of the form in which they are used, they have the structure of relatively thin cast sections which have cooled at different rates depending upon the size, thermal conductivity and amount of pre-heating of the parts to be joined. It is difficult to cast test specimens comparable to these thin sections, but some idea of their malleability and ductility can be expressed by stating that a good silver solder should stand at least 50 per cent reduction in cold working when cast in a chill mold, without any indication of cracking.

Tensile Strength:

The tensile strength of silver solders as cast will vary from 40,000 to 60,000 lb. per sq. in. Tensile strength and elongation of a large number of small cast bars having a cross-section 0.100 by 0.300 in. are given in Table II. These bars were cast in iron molds and the rate of chilling was probably much more rapid than when the solder is used. The elongation figures were very erratic and examination of the surfaces at the break showed that this was partly accounted for by too rapid chilling and consequent unsound castings.

TABLE II.—PHYSICAL PROPERTIES AND ELECTRICAL CONDUCTIVITY OF SILVER SOLDERS.

Chemical Composition					Specific Gravity, as Cast	Physical Properties, as Cast		Electrical Conductivity	
Silver, per cent	Copper, per cent	Zinc, per cent	Cadmium, per cent	Nickel, per cent		Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Conductivity (copper, 100 per cent)	Resistance, microhms per cu. cm.
9.0	51.0	40.0	....	....	8.55	48 800	16.0	20.5	8.33
20.0	45.0	30.0	5.0	....	8.80	53 000	12.0	24.4	7.69
25.0	52.5	22.5	....	....	8.94	.....	....	24.4	7.69
30.0	38.0	32.0	....	....	8.86	.....	....	24.4	7.69
40.0	30.0	28.0	....	2.0	9.04	.....	....	16.8	10.17
40.0	36.0	24.0	....	....	9.11	57 800	6.2	19.7	8.65
45.0	30.0	25.0	....	....	9.15	.....	....	19.0	8.97
46.0	38.5	15.5	....	....	....	49 900	9.0	....	....
47.0	29.0	24.0	....	....	....	58 500	16.0	....	....
50.0	28.0	22.0	....	....	9.22	.....	....	19.7	8.65
50.0	32.5	17.5	....	....	....	55 500	9.0	....	....
50.0	34.0	16.0	....	....	....	.....	....	24.1	7.04
60.0	25.0	15.0	....	....	9.52	64 300	7.7	20.5	8.33
65.0	20.0	15.0	....	....	9.60	64 800	34.0	21.3	8.01
70.0	30.0	....	....	....	....	57 500	25.0	....	....
70.0	25.0	5.0	....	....	....	50 300	9.5	....	....
70.0	20.0	10.0	....	....	9.76	.....	....	26.7	6.41
72.0	28.0	....	....	....	9.95	.....	....	77.1	2.24
75.0	20.0	5.0	....	....	9.92	.....	....	38.1	4.48
75.0	22.0	3.0	....	....	10.03	41 800	5.3	53.4	3.20
80.0	16.0	4.0	....	....	10.05	50 100	16.0	45.8	3.73
100.0	.....	....	....	....	....	.....	....	106.7	1.60
.....	100.0	....	....	....	....	.....	....	100.0	1.71

Corrosion Resistance:

Silver solders resist ordinary atmospheric corrosion, but there are so many factors to be considered in corrosion problems that it is difficult to make any specific statements. In general, these solders are as resistant to corrosion as the non-ferrous metals and alloys which are used for their corrosion-resisting properties. They are used extensively in the manufacture of chemical apparatus and the silver-copper eutectic, which melts at 1435° F., can be used as a silver solder in those cases where the presence of zinc is harmful. They are attacked by nitric acid and discolored by sulfur.

Electrical Conductivity:

The electrical conductivity of silver solders will depend upon the percentage of zinc in the solder. Table II gives the conductivity of various compositions.

Specific Gravity:

Table II also gives the specific gravity of a number of different silver solders.

METHODS OF USING SILVER SOLDERS

The following paragraphs outline briefly the general procedure for the proper use of silver solders.

Heating:

The heat required to melt silver solders makes it necessary to use some form of torch, furnace or electrical-resistance heating in order to obtain satisfactory joints.

Torches designed to use air and gas, oxygen and gas, or oxygen and acetylene will give satisfactory results. The flame from the air-gas torch gives the least heat and there is a tendency to use an oxidizing flame in order to get as much heat as possible, which causes oxidation of the metals along the joint. The oxygen-gas torch gives a hotter flame than the air-gas and is much faster. The flame can be controlled to better advantage and in general less pre-heating is required than with the air-gas torch. Oxyacetylene torches have been developed to such a degree that they are to be preferred to all other types. High temperatures can be obtained with a reducing flame and the operator has a very flexible and easily controlled method of heating. Moreover the pre-heating of the entire mass of large pieces for some distance from the joint is not necessary and the time required for making a joint is much shorter.

It is desirable to keep the torch moving to prevent over-heating in spots and also to be careful that the torch does not blow the flux away, leaving bare sections along the joint which may become oxidized. The solder should not be brought under the torch flame until the joint is heated above the flow point of the solder.

Furnaces can be used for silver soldering when it is possible to assemble the parts with the solder and flux either in or along the joint. The furnaces are usually of the box or muffle type and can be heated by gas, oil or electricity. Specially designed furnaces are available in which the heating chamber is filled with hydrogen or a mixture of gases which prevent oxidation. It is necessary to heat the entire mass of the parts to be soldered above the flow point of the solder and unless the atmosphere in the furnace is non-oxidizing any exposed parts must have a protective coating of flux.

Resistance heating on the general principle of spot welding is an excellent method. The size of the apparatus depends upon the work to be done, but the pressure applied to the joint in this method of soldering is a decided advantage and the maximum heat is developed at the joint where it is needed.

TABLE III.—FLUIDITY OF BORAX AND BORIC ACID MIXTURES.

	BORAX	75 PER CENT BORAX, 25 PER CENT BORIC ACID	50 PER CENT BORAX, 50 PER CENT BORIC ACID	25 PER CENT BORAX, 75 PER CENT BORIC ACID	BORIC ACID
Begins to thicken at.	1400° F.	1490° F.	1510° F.	1510° F.	1600° F.
Decidedly viscous at	1330° F.	1440° F.	1460° F.	1470° F.	1510° F.
Extremely viscous at	....	1300° F.	1325° F.	1325° F.	1280° F.
Almost solid at.....	1165° F.	1240° F.	1250° F.	1220° F.	1160° F.
Solid at............	1125° F.	1120° F.	1160° F.	1140° F.	1050° F.

Pieces of wire can be joined by dipping the ends into a small crucible containing molten solder. The solder should be protected with flux and the ends of the wire held firmly together when removed from the solder.

Fluxes:

The flux acts as a protection against oxidation, dissolves oxides which may form during heating, and assists in the free flowing of the solder. The exact scientific explanation of the last-named function of the flux is somewhat obscure, but it is probably due to some effect that the flux has on the surface tension of the solder. It is evident, therefore, that a good flux should be liquid at the soldering temperature and have a minimum tendency to volatilize at this temperature. Borax is the most common flux used with silver solders. Commercial powdered borax contains approximately 47 per cent of water of crystallization, which causes a bubbling action during heating. This action is not serious in most soldering operations but can be avoided by using fused borax. Owing to the fact that fused borax will rapidly take up this water of crystallization, it is necessary to use some other vehicle than water if it is desired to make a paste or solution of the fused borax. There are many special fluxes which contain borax, boric acid, phosphoric acid and other chemicals. Saturated solutions of sodium cyanide or potassium cyanide with a small percentage of borax or boric acid are convenient for small work, but they do not have the fluxing properties of borax.

For ordinary purposes, borax or a combination of borax and boric acid will meet all requirements. Experience has shown that the fluidity of the flux has an important bearing on the soldering operation and Table III gives the relative fluidity of borax, boric acid and combinations of these salts at different temperatures. There are no sharp thermal effects observable, but there is a decided change in the consistency of the flux at the temperatures given in this table. Tests have also shown that boric acid will have to be heated to 1600°F. to be as fluid as borax is at 1400°F. Slightly above 1400°F., however, borax is much more fluid than boric acid ever becomes in the range of brazing temperatures. The function of the boric acid seems to be principally to make a more viscous flux which at high temperatures does not run so freely as borax and offers a better protection against oxidation; but it does not dissolve oxides as readily as borax.

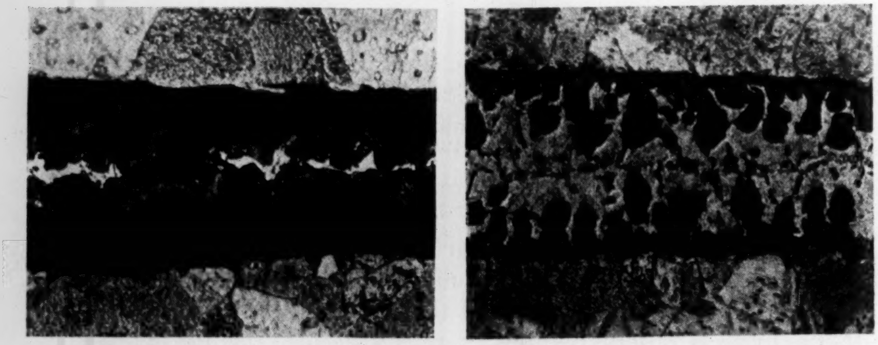
As it requires approximately a temperature of 1400°F. to make borax a thin liquid, this flux is a good temperature indicator for the user of silver solders, because if the borax is not thin there is a chance for the irregular flowing of the solder around the joint and there are likely to be inclusions of borax.

Stainless steels, or any alloys containing an appreciable amount of chromium, require special fluxes. A flux composed of equal parts of borax and boric acid made into a paste with a saturated zinc chloride solution is better than borax for use with stainless steels. This flux can also be made by using zinc chloride crystals, fused borax and boric acid which can be thoroughly mixed and ground together. If it is desired to use this latter composition in paste form it will be necessary to use alcohol, because the addition of water would cause the fused borax to cake.

The alkali bi-fluorides can also be used for dissolving refractory oxides which are not readily dissolved in borax. Different proportions of these bi-fluorides with borax can be used, but the proportion of about equal parts of bi-fluoride and borax will prove quite satisfactory.

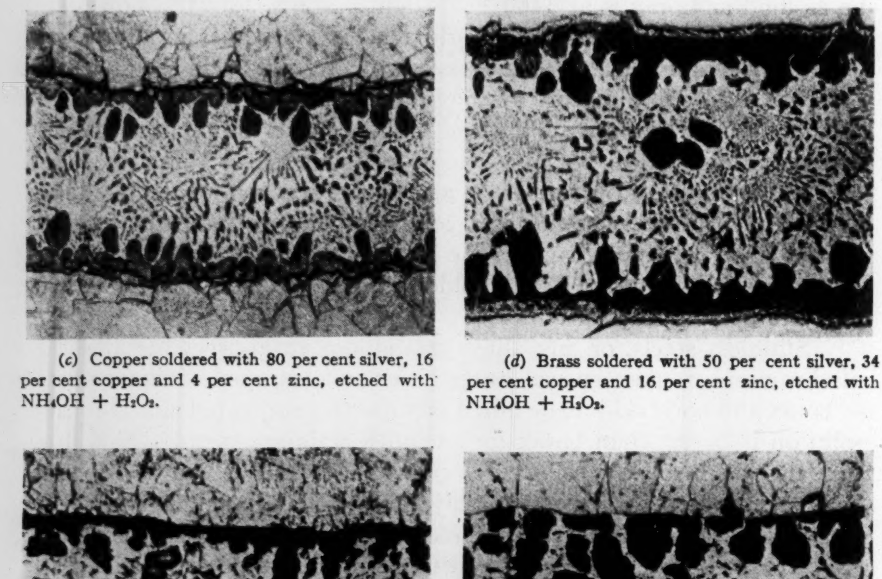
JOINING METALS AND ALLOYS WITH SILVER SOLDERS

Important factors involved in making joints with silver solders are: surface phenomena in metals and alloys, capillary attraction,



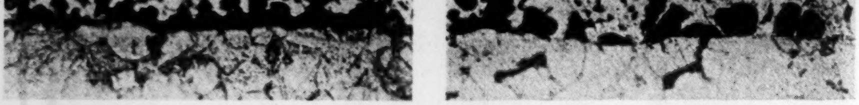
(*a*) Copper soldered with 9 per cent silver, 51 per cent copper and 40 per cent zinc, etched with $NH_4OH + H_2O_2$.

(*b*) Copper soldered with 45 per cent silver, 30 per cent copper and 25 per cent zinc, etched with $NH_4OH + H_2O_2$.



(*c*) Copper soldered with 80 per cent silver, 16 per cent copper and 4 per cent zinc, etched with $NH_4OH + H_2O_2$.

(*d*) Brass soldered with 50 per cent silver, 34 per cent copper and 16 per cent zinc, etched with $NH_4OH + H_2O_2$.



(*e*) Nickel silver soldered with 50 per cent silver, 34 per cent copper and 16 per cent zinc, etched with acid ferric chloride.

(*f*) Iron soldered with 50 per cent silver, 34 per cent copper and 16 per cent zinc, etched with $NH_4OH + H_2O_2$.

FIG. 2.—Photomicrographs of Various Silver-Solder Joints (× 500).

rate of diffusion at different temperatures, thermal conductivity, effect of pressure during soldering, fluidity of flux and susceptibility of metals to oxidation at temperatures above red heat.

The joints should be clean because the wetting of the surface is the most important factor in silver soldering. Although the flux will dissolve films of oxide it is better to start with clean joints. It is also advisable to have the joints well fitted. Silver solders flow freely and better results will be obtained when the joints contain a minimum amount of solder.

All parts of the joint and solder should be protected with the flux. One of the most satisfactory methods of applying borax flux is to make a hot saturated solution of borax and brush the solution along the joints to be soldered. This method gives an even coating of the flux, and is much more satisfactory than dipping the article into the solution. When the flux is sprinkled along the joint as a dry powder, it is important to see that the powder is sprinkled evenly and that it is not blown away by the torch flame, leaving places exposed for oxidation. With care it is possible to heat the joint to a degree where the powdered borax will stick and at the same time oxidation will not have occurred sufficiently to be harmful. Fluxes which are made in paste form are easy to apply to the joint with a stiff brush.

It is necessary to bring the joint above the temperature of the flow point of the solder and to have the flux a thin fluid before the solder is brought under the torch flame. One of the worst conditions is to heat the joint to a temperature just below the flow point of the solder for a relatively long period of time. Oxidation at these temperatures is rapid, and although the flux will dissolve these oxides it tends to become more viscous and does not assist to the same degree in the rapid flowing of the solder.

The amount of diffusion of the solder in most cases is slight, but it varies according to the temperature, composition of the solders and composition of the metals and alloys which are being soldered. This diffusion is a time-temperature reaction and the photomicrographs, Fig. 2, are given to show how this diffusion varies with different solders.

Pressure assists materially in getting tight joints. Whenever possible the parts to be joined should be held in jigs which will insure that they will be pressed firmly together. A great many joints are made with silver solders when it is not possible to apply pressure and in those cases it is particularly important to see that the temperature is sufficiently high to prevent inclusions of the flux being left in the joint.

The thermal conductivity of different metals and alloys must be given careful consideration because the amount of pre-heating required depends upon this factor. When soldering metals of high conductivity more pre-heating is required in order to make sure that when the solder is flowing the heat will not be conducted away from the joint too rapidly. The size and shape of the pieces to be joined also has an important bearing upon the amount of pre-heating necessary.

Silver soldering is an art which requires skill, but it is not difficult when proper attention is given to heating of the joint and use of the flux. The temperature chart for fluxes (Table III) shows how quickly borax becomes viscous at temperatures below 1400°F. and if the temperature of the joint falls below this point there are likely to be small inclusions of the borax in the joint which after a period of time will cause leaks.

When these points are given proper consideration silver solders will wet the surface of the metal, flow quickly, and make strong tight joints.

Brass:

Strong ductile joints can be made on all compositions of brass, either cast or wrought. The melting points of different compositions of brass will run from approximately 1560°F. for extruded brass to 1850°F. for the low brasses and bronzes, depending upon the composition. The relatively low melting points of some of the brasses justify the use of high-grade solders in order to prevent damage to the brasses from over-heating. Although it is possible to join common high brass with silver solder containing 10 per cent silver and high zinc, it is better to use a grade containing at least 20 per cent silver, and when thin sections or small pieces are to be joined higher grades are to be preferred because of their low melting points. Twenty per cent of silver is the lowest grade that should be considered for use with extruded brass or bronze if a reasonable factor of safety below the melting point of the bronze is allowed.

Brass can be joined to steel, iron, copper, nickel silver and non-ferrous alloys having melting points above 1400°F.

Borax is a satisfactory flux.

Copper:

The melting point of copper is 1981°F. and all grades of silver solders can be used, but there are many instances where the solders containing the higher percentages of silver are to be preferred. Copper conducts heat rapidly and high-grade silver solders with low flow points are much safer to use with thin sections and tubing and in all places where grain growth due to high temperatures would be detrimental. When joining copper rods or sheet which are to be cold-worked to any extent, it is better to use a high-grade silver solder containing small percentages of zinc. Silver solders containing 60 to 80 per cent of silver are used depending upon the amount of cold work to be done.

When using a torch on thin sections of copper tubing it is important to prevent overheating in spots and at the same time heat the joint to the proper temperature to obtain a free flowing of the silver solder and prevent inclusions of the flux. This point is emphasized because experience has shown that in many cases sufficient care is not taken in controlling the temperature.

Borax is a satisfactory flux.

Nickel Silver:

Silver solders are used extensively with different grades of nickel silver. The melting point of 18-per-cent nickel silver is approximately 1955°F. and where color is not important the lower-grade solders can be used. Solders containing less than 50 per cent of silver have a light yellow color and this yellow color increases as the silver contents are reduced. Where thin sections are joined it is better to use a higher grade solder. No particular difficulty should be experienced in using silver solders with these alloys. Borax is a satisfactory flux.

Stainless Steels and Irons:

Stainless steels and irons present some difficulty to the successful use of silver solders. The heat required produces a thin film of oxide which tends to prevent proper wetting of the surface by the solder. In addition to this there is very slight, if any, diffusion of the silver solder. It is impossible to make a silver solder having the same color as stainless steel. Sheet metal can be joined by making lap joints or scarf joints. Butt joints on thin sheets when subjected to severe bending stresses are likely to fail. If wide sheets are to be joined it is necessary to hold the sheets firmly in clamps to prevent warping. The application of pressure is of particular assistance in making joints on these metals. Silver solders containing 10 per cent or less of silver and relatively high zinc content give better results than solders that contain over 50 per cent of silver.

By the addition of small percentages of nickel it is possible to produce a silver solder which contains between 40 and 50 per cent of silver, flows below 1450°F., has a white color and makes strong joints.

The low-silver alloys are yellow in color and require a temperature of approximately 1600°F. for their use. Experiments have shown that even when using silver solders with lower flow points, it is desirable to work at temperatures from 1550°F. and above.

Special fluxes must be used as mentioned above under fluxes.

Iron and Steel:

Strong joints in iron and steel can be made with all grades of silver solders. Cast iron, wrought iron, carbon steels in sheet or strip form can be joined to each other or to brass, copper, nickel silver and other non-ferrous metals.

Silver solders are used in those cases where strength and ductility are important and the higher temperatures required for the use of spelter solders would be injurious. This is particularly true when non-ferrous alloys having relatively low melting points are joined to steel or iron parts. The use of silver solders for joining steel band saws is a typical example where they are extensively used, because they melt at lower temperatures than base-metal brazing solders and make strong joints which stand the heavy stresses to which band saws are subjected.

Borax or a combination of borax and boric acid are the common fluxes used with iron and steel.

Monel Metal and Nickel:

Silver solders can be used to advantage on both monel metal and nickel. The corrosion resistance, color, strength and ductility of silver solders make them particularly applicable for use with these metals. Although the color does not exactly match monel metal and nickel, a good appearance can be obtained when making silver-soldered seams.

Tests made in the laboratories of the International Nickel Co. show that there is a decided lowering of the ductility of monel metal if it is in contact with silver solders at temperatures over 1350 to 1450°F. This effect is not appreciable with nickel. The heating of monel metal, therefore, should be kept as local as possible by the use of small flames, except in those cases where complete even heating can be obtained as in furnace work. Uneven heating of monel metal in large areas by a torch flame is likely to cause cracking and particular care must be taken with both nickel and monel metal to prevent oxidation, which will interfere with the proper adherence of the silver solder.

Tests show that the corrosion resistance of silver-soldered joints compares favorably with either monel metal or nickel. In some cases the joints are slightly protected galvanically and this quality is an important consideration in seams. Silver-soldered joints with both monel metal and nickel show high tensile strength and closely approach the best welded seam structurally.

Silver solder is used with monel metal for fastening turbine blades in place and in the manufacture of dyeing and laundry machinery, tanks, furniture for hotels, hospitals and restaurants. When making extra long lengths of monel wire, the wire may be silver soldered and then drawn so that the finished product is difficult to distinguish from a homogeneous wire. Silver solder is used with pure nickel in the manufacture of dairy and food-handling equipment and for joining seamless nickel tubing.

Flux is used not only along the joint but on adjacent areas to prevent oxidation of the surface and thus make it easier to produce highly polished surfaces when refinishing. A flux containing as much as four parts of boric acid to one of borax is recommended by some users. The advantage of this large amount of boric acid is probably the greater protection afforded against oxidation.

Aluminum Bronze:

Aluminum bronze can be soldered with silver solders, but the film of oxide which forms interferes seriously with making good joints. Care is required in the use of the heating and fluxing as in the case of stainless steels. Fluxes recommended for stainless steels should be used.

SPECIAL SILVER SOLDERS

It seems logical to assume that if a few standard compositions of silver solders would cover the industrial requirements, it is an economic waste to make a large number of special mixtures. There may be cases where none of the standard solders covered by the Society's Specification B 73 – 28 T will meet the requirements, but in many instances it will be found that the development of a special solder could be avoided if proper attention is given to the art of using the standard solders.

There is a wide gap, however, between the flow points of the soft solders and silver solders. It is possible to produce silver alloys which have flow points scattered through a temperature range of 500 to 1300°F. Some of these alloys which flow around 700 to 900°F. are ductile, but the solidus or melting point is approximately the same as in soft solders and the physical characteristics are more like those of soft solders than of hard solders. Alloys can be made with these same flow points and having much higher melting points, but they are brittle and joints made with them will not stand heavy stresses. Moreover the question of flux for these alloys is very important, particularly if the heating is to be done with torches. The ordinary fluxes used for soft solders burn off and are not satisfactory; the fluxes suitable for hard solders cannot be used, or if they are used it means that the benefit of the low flow point of the solder is not obtained.

Table IV gives the melting and flow points of a few compositions taken at random to illustrate the problem involved in producing these alloys of low melting point.

Table IV.—Low-Melting Silver Alloys.

Chemical Composition, per cent					Melting Point, deg.Fahr.	Flow Point, deg.Fahr.	Cold Working Properties
Silver	Cadmium	Zinc	Tin	Copper			
5.0	78.4	16.6	....	....	480	600	50-per-cent reduction
15.0	70.0	15.0	....	....	520	750	50-per-cent reduction
20.0	66.0	14.0	....	....	640	850	Brittle
20.0	30.0	....	50.0	....	420	780	½ in to 0.030 in. without annealing
40.0	....	6.0	40.0	14.0	690	800	Brittle
30.0	....	30.0	40.0	....	860	1060	50-per-cent reduction, but cracks on edge
20.0	....	50.0	30.0	....	650	970	50-per-cent reduction, but cracks on edge

These alloys may be useful in some particular field where the high strength of standard silver solders is not necessary. The large number of different combinations which it is possible to make precludes more discussion in this paper.

Acknowledgment.—The author desires to express his appreciation of the assistance of the members of Subcommittee XIV on Precious Metals and Alloys of the Society's Committee B-2 on Non-Ferrous Metals and Alloys in the preparation of this paper and particularly to Mr. C. H. Chatfield, Research Metallurgist for Handy & Harman for the photomicrographs and physical tests, and to Handy & Harman for their courtesy in allowing the publication of these data.

DISCUSSION

Mr. R. J. McKay[1] (*presented in written form*).—Mr. Leach's discussion of one of the well-known joining materials is particularly timely now when new uses and new types of construction are daily occurrences in the field of corrosion-resisting alloys. Certain properties of silver solders make them particularly suitable for joints subject to corrosion.

I would emphasize the importance and need of strong corrosion-resisting joints in apparatus intended to stand severe service conditions. Too often the joint has been the point of failure. A good joining material should be physically strong and malleable, it should be capable of application without damage to the metal being joined and it should not only be corrosion resisting in itself but should be galvanically cathodic toward the metal joined.

The localization of corrosion in joints is now reasonably well understood. It occurs either by concentration cell attack or by galvanic differences between the joining metal and that joined. Concentration cells may be avoided by obvious methods. Since galvanic attack is partially inherent in the metals it cannot be easily controlled by design. However, since galvanic attack is roughly proportional to the areas involved the best protection to the whole apparatus is obtained with cathodic joining material. The area of this material being small in comparison to the other exposed metal, the slightly increased attack on the metal joint is usually insignificant for all practical purposes. Silver solder has a relatively noble composition among metals in many solutions and is thus useful for joining the metals used in highly corrosive conditions as, for instance, monel metal and the nickel-chromium iron alloys. High silver solders are cathodic to monel metal under most corrosive conditions and they are cathodic to nickel-chromium-iron alloys under many of the conditions where these metals are useful. The galvanic position of the nickel-chromium-iron alloys varies more drastically in different solutions than do most alloys and in such conditions as contact with strong nitric acid the situation is reversed and silver solder seams are very rapidly attacked.

The practical mechanism of applying silver solder to monel metal and the nickel-chromium-iron alloys has some advantages and some disadvantages. High-melting-point silver solders cause severe intercrystalline attack on monel metal resulting in almost certain failure if they are applied to metal which is in a strained condition. The same phenomenon seems to occur with the nickel-chromium-iron alloys, and the cure for it is, as indicated in Mr. Leach's paper, the use of a brazing material at temperatures either above or below the danger range. It is practical to get below the range in both cases with low-melting-point solders if care is taken not to heat the metal too high and if heating is done either very locally or over broad areas so that strains are evenly distributed. Mr. Leach states that the difficulty may be removed on stainless steels and iron by heating at 1550° F. and above. This temperature is not out of the danger range for carbide precipitation and, therefore, I believe better results are obtained by the use of considerably higher temperatures, say not under 1800° F. Soldering at these temperatures is advisable on monel metal, of course, for other reasons than freedom from carbide precipitation. Temperatures of 1800° F. and over are out of the true silver solder range and the ordinary brazing alloys melting at these temperatures are not sufficiently corrosion resistant and are galvanically too anodic for wide use with these corrosion-resistant materials. Thus the problem of a hard solder for brazing material really suitable for these metals has not yet been satisfactorily solved.

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[1] Superintendent of Technical Service, International Nickel Co., New York City.

MR. T. A. WRIGHT[1] (*presented in written form*).—The paper by Mr. Leach is a very able and helpful one and should help to eliminate a number of cases of faulty practice in the choice and use of silver solders.

In this and in other discussions in connection with the work of Subcommittee XIV of the Society's Committee B-2 on Non-Ferrous Metals and Alloys, leading towards the adoption of standard specifications for these alloys, Mr. Leach has brought out clearly the importance of choosing the right solder.

It would be interesting to have his comments upon the question of soldering sterling silver which had not been thoroughly or efficiently deoxidized. The writer has noted in attempting to solder sterling which was not deoxidized, although with clean appearing surface, that a solder which worked efficiently on good metal tended to collect in balls and not wet the surface or flatten out as it should. The writer would appreciate comments from Mr. Leach as to whether in his opinion it might be possible that the reducing flame of the torch reduces the oxides in the metal to form a vapor which might cause this effect.

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[1] Technical Director and Secretary, Lucius Pitkin, Inc., New York City.

In connection with the interesting photomicrograph of various silver solder joints as given in Fig. 2 of the paper, the writer would appreciate knowing if Mr. Leach had examined any silver soldered joints made under pressure in a hydrogen or controlled atmosphere furnace. Reference is made on page 500 to the use of this type of furnace, which incidentally is growing in the jewelry industry, and the question of pressure is touched upon in the last paragraph of page 503.

An experience that came to the attention of the writer may be of interest. Sterling silver which had not been thoroughly deoxidized in the melting was being annealed in a hydrogen annealing furnace. The particular furnace being used does not always operate efficiently and partial oxidation occurred in one zone of the furnace followed by reduction by means of the hydrogen in another part. The sterling silver came out with a pink case due to a more or less thin film of copper. So far as the records show samples of the material with the copper film gave joints of normal strength and normal soldering characteristics. It was noted that similar sterling annealed in either an electric muffle or open gas flame furnace gave trouble in soldering.

MR. R. H. LEACH.[1]—The reduction of any oxides by the reducing flame of a torch would unquestionably produce gases, but from my experience I could not say that this would cause the solder to collect in balls and not wet the surface as it should. In most cases, balling is caused by thin films of oxide or too low temperatures. Films of oxide so thin that they cannot be seen are quite sufficient to prevent free flowing of the solder. The slagging action of the flux is a time and temperature reaction and the higher the temperature the quicker the flux will remove any oxides. I think that the trouble referred to by Mr. Wright is probably due to the fact that the flux did not thoroughly clean the oxide from the surfaces to be joined.

I have not made any microscopic examinations of joints made under pressure in a hydrogen furnace, but I should expect that under these conditions the relatively thin sheet of solder which would be used would be almost entirely diffused. All of our microscopic work indicates that this diffusion is dependent principally upon time and temperature, but a slight pressure seems to be advantageous.

Mr. Wright's remarks about soldering sterling silver which has a thin film of copper due to the reduction of copper oxide by hydrogen are logical. When the oxide is reduced there is an ideal bonding surface of clean metal, whereas, in the other furnace where the work is exposed to the air the oxide films interfere with soldering.

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[1] Manager of Research and Development, Handy & Harman, Bridgeport, Conn.

THE EFFECT OF ADDITIONS OF SMALL PERCENTAGES OF NICKEL TO A COPPER-TIN BRONZE

By Clair Upthegrove,[1] G. Wilson[2] and F. N. Rhines[3]

Synopsis

This paper presents the results of a laboratory study of the effect of additions of small percentages of nickel to a copper-tin bronze on the microstructure, the hardness of the microconstituents and the hardness of the alloy. The substitution of small percentages of nickel for copper results in marked changes in the microstructure, 1 per cent causing the disappearance of the alpha of the eutectoid and the appearance of a dispersed constituent in the alpha matrix. In cast alloys annealed for 120 hours at 800° C., the substitution of nickel for copper results in a continuous increase in hardness for the alpha constituent, while in the constituent corresponding to delta a decrease in hardness followed by an increase is found.

Introduction

The addition of small percentages of nickel to copper-tin bronzes has been of considerable practical interest during the past few years. This has been particularly true of additions to bronzes which are to be used as bearings. That the addition of nickel to bearing bronzes, however, is not new, is indicated by an article appearing in the *Brass World*[4] of 1907 in which reference is made to the use of a nickel-phosphor bronze for gears.

This paper presents the results of a study, started two to three years ago, of the effects of small percentages of nickel on the microstructure and on the hardness of the micro constituents. The hardness of the micro constituents was determined by means of the Bierbaum micro character.[5]

Alloys Prepared

An 85 per cent copper, 15 per cent tin alloy was selected as the base for the nickel additions, largely because it approximated the limiting solubility of the alpha solid solution and consequently might be expected to respond more readily to the nickel addition than if a lower tin content were used. Two series of alloys were prepared. Starting with an 85 per cent copper, 15 per cent tin base, chill-cast alloys were made with 0, 0.25, 0.50, 1.0, 2.0, 3.0, 5.0 and 10 per cent nickel, the nickel replacing the copper. A second series carrying 0, 1.0, 2.0, 3.0 and 5.0 per cent nickel were sand cast. Copper and tin were determined for six of the alloys and found to check very closely the computed compositions.

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[1] Professor of Metallurgical Engineering, Deparment of Chemical Engineering, University of Michigan, Ann Arbor, Mich.

[2] Research Assistant, Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[3] Senior, Department of Chemical Engineering, University of Michigan, Ann Arbor, Mich.

[4] *Brass World*, Vol. 3, p. 187 (1907).

[5] C. H. Bierbaum, "A Study of Bearing Metals," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. LXIX, p. 972 (1923).

HARDNESS DETERMINATIONS

The chill-cast alloys, which were cast as 1-in. rounds, were sectioned and specimens prepared for micro-character hardness tests. Due to the finely divided condition of the eutectoid, difficulty was encountered in obtaining consistent readings for the micro hardness. Sand-cast specimens were then prepared and micro-character tests made. While the difficulties encountered with the chill-cast specimens were eliminated, the results obtained did not in all cases appear to be consistent with the changes in composition. This lack of consistency in the results obtained was assumed to be due to variations in casting conditions, although these were controlled as carefully as possible.

As the primary purpose of the investigation was to determine the effect of the nickel on the hardness of the micro constituents and as this effect presumably was related to the solubility of the nickel and the tin in the copper, it was decided to anneal the chill-cast specimens. By annealing, the alpha solid solution would be permitted to approach more closely to equilibrium, a more complete separation of the eutectoid would be made possible and the differences due to casting conditions would be eliminated. The effect of the nickel would then be more readily determined.

The alloys were annealed for 120 hours at 800° C. or very close to the softening range and cooled slowly in the furnace.

As neither the accepted copper-tin diagram or the nickel-tin diagram gave any indication that there would be any lowering of solubility for the alpha solid solution, the rate of cooling was purposely made very slow in order to favor the eutectoid inversion. As a result the alloys carrying the higher percentages of nickel no longer showed a homogeneous alpha constituent. This confirmed the experience of Price, Grant and Phillips[1] who found that a 90 per cent copper, 10 per cent nickel base alloy to which 8.3 per cent tin had been added when heated to 800° C. and cooled slowly showed not beta but was "peppered with a second constituent."

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[1] W. B. Price, C. G. Grant and A. J. Phillips, "Alpha Phase Boundary of the Copper-Nickel-Tin System," Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 503 (1928).

Following the annealing treatment, Rockwell hardness tests were made on each of the alloys and Bierbaum micro-character tests on

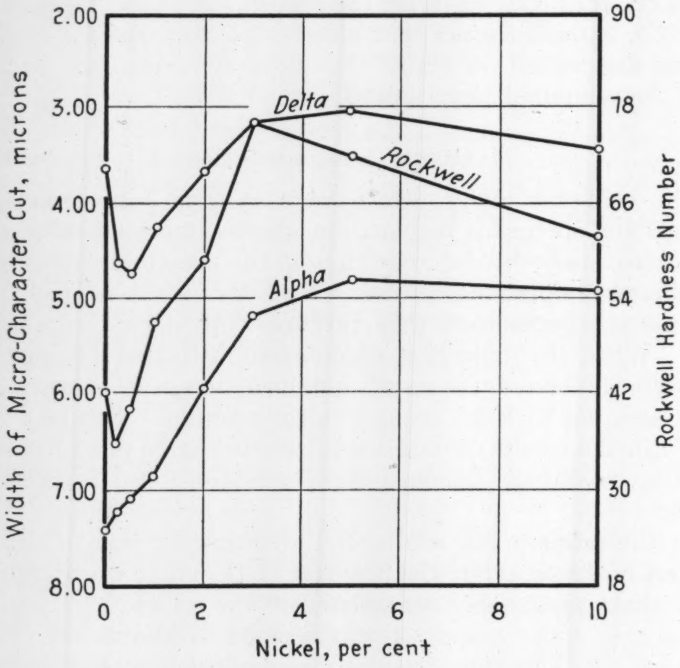


FIG. 1.—Showing Effects on Micro-Character Hardness of the Addition of Nickel.

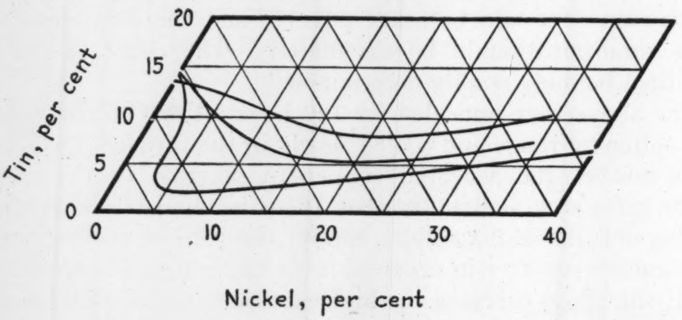


FIG. 2.—Alpha Phase Boundary by E. M. Wise for Copper-Nickel-Tin Alloys.

the alpha and the delta constituents, though as the nickel content was increased, the tests may perhaps more properly be said to have been made on an alpha constituent, through which a second was dispersed, and on a constituent corresponding to the delta of the copper-tin alloys. The results of these tests are shown in Fig. 1. Micro-character hardness values have been plotted as width of the cut in microns, rather than as Bierbaum hardness numbers.

The hardness of the delta constituent and the hardness of the alloy are both found to decrease with the first additions of nickel. In the delta the original hardness is reached only after approximately 1¾ per cent of nickel is substituted for copper. A maximum effect is obtained at 5 per cent. The alpha constituent, however, is found to increase continuously with increasing nickel up to 5 per cent. While the alpha and the delta show a different behavior with the first addition of nickel, once the nickel is present to the extent of 0.25 per cent the two constituents increase at practically a constant rate up to 5 per cent nickel. This may be seen from Table I giving the ratio of the width of alpha cut to the width of the delta cut.

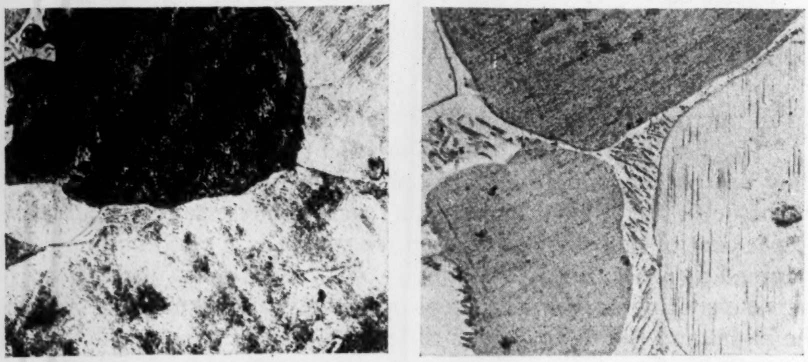
TABLE I.—SHOWING EFFECT OF ADDITION OF NICKEL ON MICRO-CHARACTER HARDNESS.

	WIDTH OF MICRO-CHARACTER CUT, MICRONS		
NICKEL, PER CENT	ALPHA	DELTA	RATIO, ALPHA TO DELTA
0	7.48	3.62	1.96
¼	7.22	4.64	1.56
½	7.09	4.73	1.50
1	6.84	4.26	1.60
2	5.93	3.66	1.62
3	5.20	3.18	1.62
5	4.81	3.05	1.58
10	4.94	3.44	1.44

While increasing the hardness of the alpha, the substitution of the nickel for the copper has resulted in a very noticeable decrease in the ratio of the hardness of the delta to the alpha. With 10 per cent of nickel substituted for the copper the alpha and delta no longer increase in hardness and the ratio falls still lower.

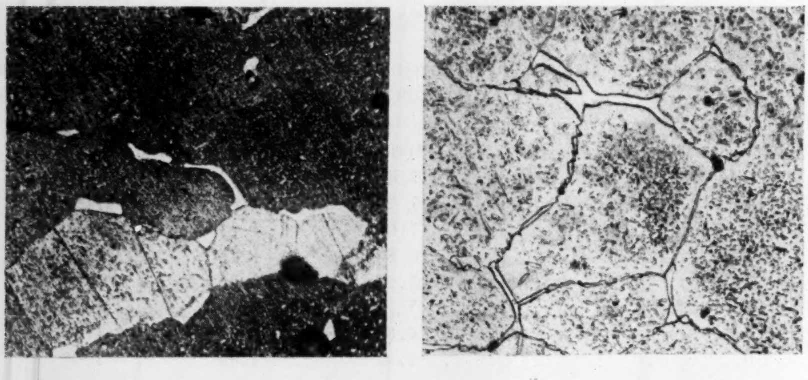
MICROSTRUCTURE

Typical microstructures are shown in Figs. 3 to 5. With ½ per cent of nickel the eutectoid is present and somewhat more pronounced than in the alloy containing no nickel. With 1 per cent nickel two changes are evident in the structure. The alpha of the eutectoid has practically disappeared and a dispersed constituent is found in the alpha. With increasing nickel content the dispersed constituent in the alpha becomes more pronounced and at 3 per cent the alpha appears to be peppered with this second constituent. Further increase in the nickel content results in an increase in the amount and size of the dispersed constituent.



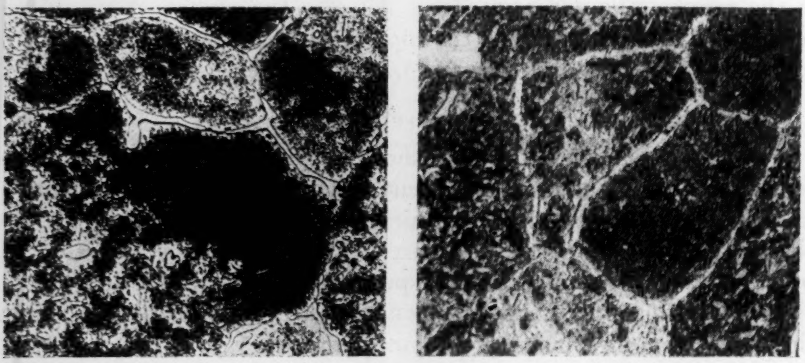
(*a*) 85 per cent copper, 15 per cent tin.

(*b*) 84.5 per cent copper, 15 per cent tin, 0.5 per cent nickel.



(*c*) 84 per cent copper, 15 per cent tin, 1.0 per cent nickel.

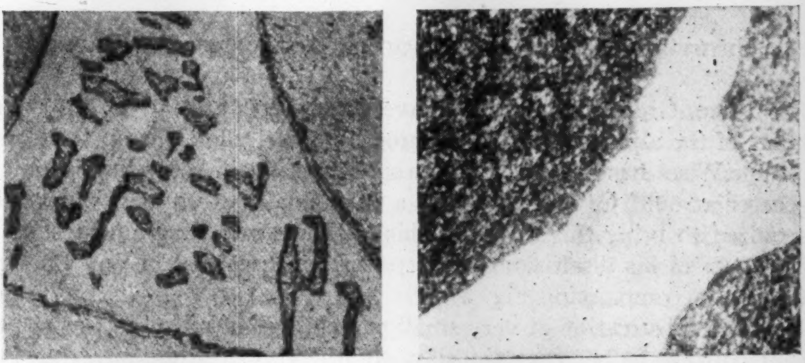
(*d*) 83 per cent copper, 15 per cent tin, 2.0 per cent nickel.



(*e*) 82 per cent copper, 15 per cent tin, 3.0 per cent nickel.

(*f*) 80 per cent copper, 15 per cent tin, 5 per cent nickel.

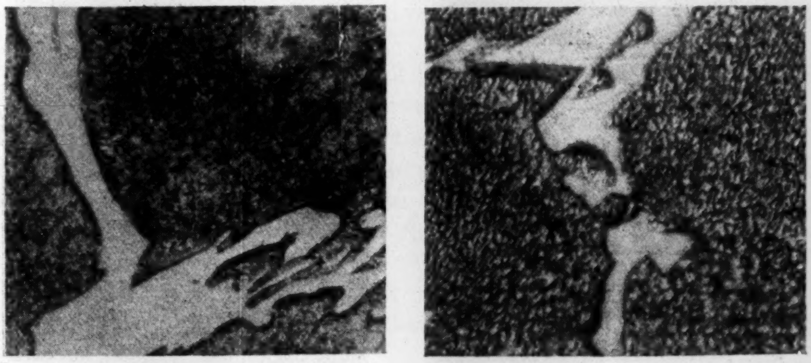
FIG. 3.—Photomicrographs of Alloys Annealed 120 hours at 800° C. (× 100). All samples etched with NH_4OH and H_2O_2 and acid $FeCl_3$.



(*a*) 84.5 per cent copper, 15 per cent tin, 0.5 per cent nickel.

(*b*) 84.0 per cent copper, 15 per cent tin, 1.0 per cent nickel.

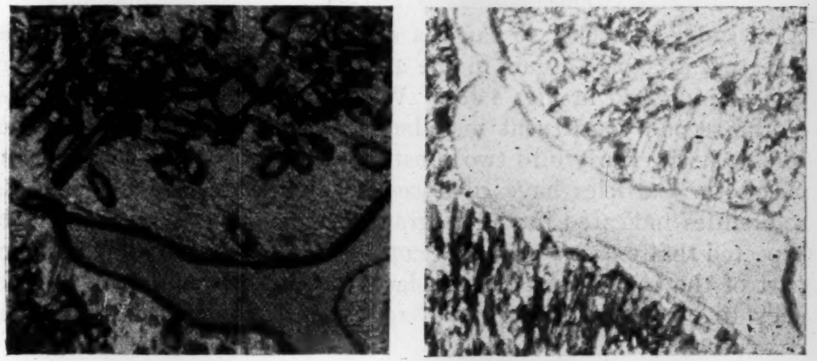
Annealed 120 hours at 800° C.



(*c*) 80 per cent copper, 15 per cent tin, 5 per cent nickel.

(*d*) 86 per cent copper, 11 per cent tin, 3 per cent nickel.

Sand Cast.



(*e*) 82 per cent copper, 15 per cent tin, 3 per cent nickel.

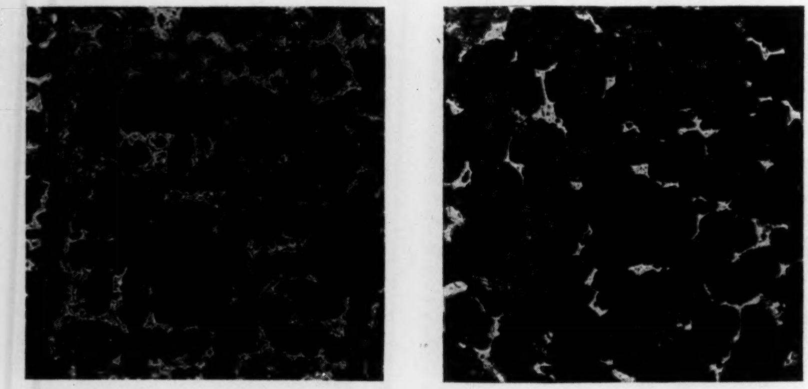
(*f*) 80 per cent copper, 15 per cent tin, 5 per cent nickel.

Annealed 120 hours at 800° C.

FIG. 4.—Photomicrographs of Alloys (× 1000). All samples etched with NH_4OH and H_2O_2 and acid $FeCl_3$.

Price, Grant and Phillips[1] have shown that at 800° C. the solubility of the alpha solution is lowered by nickel additions up to 20 per cent. Wise[2] has indicated that this reduction in solubility is much greater at 300° C. and that only a very small percentage of nickel is required to bring this about. This is shown in a diagram presented as a part of his discussion of the paper by Price, Grant and Phillips (see the accompanying Fig. 2).

The substitution of very small percentages of nickel in the 85 per cent copper, 15 per cent tin alloy for the copper while affecting the hardness of the micro constituents does not make itself evident in the microstructure except from the increased percentage of eutectoid. With sufficient nickel to cause a disappearance of the alpha of the eutectoid a change occurs in the appearance of the alpha solid solution as indicated in Fig. 4 (*b*). While one or two definite particles of the second constituent may be seen, most of the field does not resolve itself clearly into two constituents. With 3 per cent or more nickel the particles have coalesced to appreciable size. From the solubilities indicated in the diagram presented by Wise it would be expected that a cast 85 per cent copper, 15 per cent tin alloy in which part of the copper had been replaced by nickel would show a tendency to precipitate a dispersed constituent through the alpha solid



(*a*) 80 per cent copper, 15 per cent tin, 5 per cent nickel.

(*b*) 86 per cent copper, 11 per cent tin, 3 per cent nickel.

FIG. 5.—Photomicrographs of Sand-Cast Alloys (× 100). All samples etched with NH_4OH and H_2O_2 and acid $FeCl_3$.

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[1] *Loc. cit.*

[2] E. M. Wise, Discussion of paper by W. B. Price, C. G. Grant and A. J. Phillips on "Alpha Phase Boundry of the Copper-Nickel-Tin System," Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 503 (1928).

solution, if the nickel added was sufficient to bring about the disappearance of the alpha of the eutectoid. Similarly the substitution of 3 per cent or more of nickel for copper in an 89 per cent copper, 11 per cent tin alloy might be expected to result in this same tendency. Figures 5 (*a*) and (*b*) and 4 (*c*) and (*d*) show the structures of a sand-cast 80 per cent copper, 15 per cent tin, 5 per cent nickel alloy and a sand-cast 86 per cent copper, 11 per cent tin, 3 per cent nickel alloy at 100 and 1000 magnifications. Comparison with Fig. 4 (*a*) shows the alpha field of these two alloys to be similar to that of Fig. 4 (*b*), indicating that such an effect does occur.

SUMMARY

By way of summary, the following conclusions drawn from the results of the tests are given:

The substitution of the nickel for the copper results in the disappearance of the alpha of the eutectoid and the appearance of a dispersed constituent throughout the alpha matrix.

The hardness of the alpha solid solution is continuously increased by the substitution of nickel up to 5 per cent.

The hardness of the delta is first decreased and then increases to a maximum at 5 per cent.

The substitution of nickel for copper in an 85 per cent copper, 15 per cent tin bronze decreases the hardness ratio for the delta and alpha constituents.

For nickel substitutions of more than 0.25 per cent and not over 5 per cent, the hardness of the delta and of the alpha change at a constant rate.

The change in the hardness of the alpha is due to the precipitation of a dispersed constituent.

DISCUSSION

Mr. C. H. Bierbaum[1] (*by letter*).—This paper shows clearly that this bronze composition, when annealed at the high temperature of 800° C. has a very distinct diffusion of its constituents, an effect that is distinctly the opposite of what occurs in this alloy when in a molten state and slowly cooling. Due to the high annealing temperature, the results are very uniform, which could not have been produced without annealing. They are highly interesting and striking.

In determinations made by the writer, alloys containing a lower percentage of tin were used, varying between 10 and 11 per cent and in a sand-cast condition, a regular foundry product for bearing purposes. In this composition, to which 4 per cent of nickel had been added, the results of microhardness were as follows:

	Alpha	Secondary Alpha	Delta
Width of microcut, average, microns.....	10.62	6.12	3.65
Microhardness, average.................	90.	625.	750.

Comparing the above with other similar material, without the nickel, a distinct tendency of the softening of the alpha crystal with the introduction of nickel seemed clearly shown. This phenomenon, of course, cannot exist where the alloy is annealed.

Why Mr. Upthegrove should use the width of cut in terms of microns in his discussion of hardness is not at all apparent, since in the mathematical expression of all the hardness formulas—Brinell, Rockwell, Vickers Pyramid Diamond and also for the Shore scleroscope (if the indentations are considered instead of the rebound of ball)—we have a factor which is the reciprocal of the square of a lineal dimension of the distortion effect. It certainly seems inconsistent, when speaking of hardness, to give the softer material the higher number. The mathematical expression for hardness in every case should contain a factor representing the reciprocal of the square of a lineal dimension of the indentation or distortion. The writer, in his original formula for microhardness, introduced this factor. The reason why this factor has not been used in the foregoing is possibly due to the Bureau of Standards having introduced this inconsistency in its earlier work.

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[1] Vice-President and Consulting Engineer, Lumen Bearing Co., Buffalo, N. Y.

In the Rockwell hardness test, like all the other standard methods—Brinell, Vickers Pyramid Diamond and scleroscope—all bring into play more than one micro constituent. Therefore, there can be and is no direct relation in material of this kind between these tests and microhardness. The microhardness test should and does show a greater variation of hardness in a substance of this kind.

MR. CLAIR UPTHEGROVE[1] (*author's closure by letter*).—The use of the width of the micro cut as an indication of the effect of the nickel additions on the hardness is perhaps unfortunate in that, as pointed out by Mr. Bierbaum, it results in the softer material apparently having the higher number. Conversion of the results as given in Table I of the paper, that is, width of the micro cuts to Bierbaum hardness numbers, shows the relationship indicated under the width of micro cut to hold equally well for the hardness numbers. With 0 per cent nickel the ratio of the hardness of the alpha to the delta constituent is 0.234, with 0.25 per cent nickel the ratio is 0.413, with 5 per cent nickel, the ratio is 0.407 and with 10 per cent nickel the ratio is 0.484. The ratio of the hardness of the alpha to the delta changes sharply with the first addition of nickel and then remains a constant over the range 0.25 to 5 per cent.

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[1] Professor of Metallurgical Engineering, Department of Chemical Engineering, University of Michigan, Ann Arbor, Mich.

THE SIGNIFICANCE OF HARDNESS VALUES FOR SOME COPPER-ZINC ALLOYS

BY C. H. DAVIS[1] AND E. L. MUNSON[1]

SYNOPSIS

The effect of grain size on the hardness of both annealed and cold-worked alpha phase copper-zinc alloys has been observed. The significance of variables which affect hardness values is shown by a series of curves.

Hardness values indicate:

1. The grain size of any given annealed alloy.
2. The grain size of any given cold-worked metal if used in conjunction with the percentage of reduction.
3. The percentage of reduction of any given alloy when used with the grain size.

Hardness values for a given grain size change progressively from that of pure copper to that of the alpha alloy of lowest copper content.

The hardness value maximum near the center of the alpha range, which has been recorded by several investigators, is not observed if any given grain size is taken as a basis for the hardness - chemical composition relationship. It is evident that this reported maximum is a function of the annealing temperature and the amount of previous cold working.

INTRODUCTION

In a previous paper[2] the hardness relationships of some copper alloys were demonstrated and it was shown that these relationships varied considerably, not only with bars of the same chemical composition but also with the several alloys of the copper-zinc, copper-tin, and copper-nickel-zinc series. It was shown that these differences in the hardness relationships exist because of differences in composition, annealing temperatures and amounts of cold working.

This paper is concerned with a study of the effect on wrought alpha copper-zinc alloys of grain size, not only alone but in conjunction with cold working. The work has been undertaken with a view of obtaining an explanation of the hardness value maximum occurring near the center of the alpha range. The grain sizes of some of the copper-zinc alloys have been determined and plotted against the chemical compositions and physical properties in an endeavor to secure an answer to the problem.

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[1] The American Brass Co., Waterbury, Conn.

[2] C. H. Davis and E. L. Munson, "Hardness Relationships and Physical Properties of Some Copper Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 422 (1929).

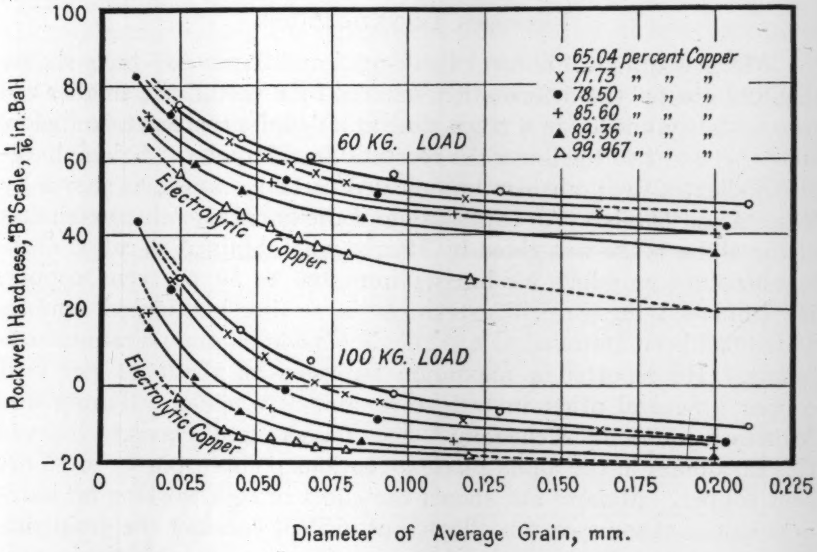

FIG. 1.—Effect of Grain Size on the Hardness of Six Copper-Zinc Alloys in the Annealed State.

The hardness values decrease as the grain size is increased in the several alloys.

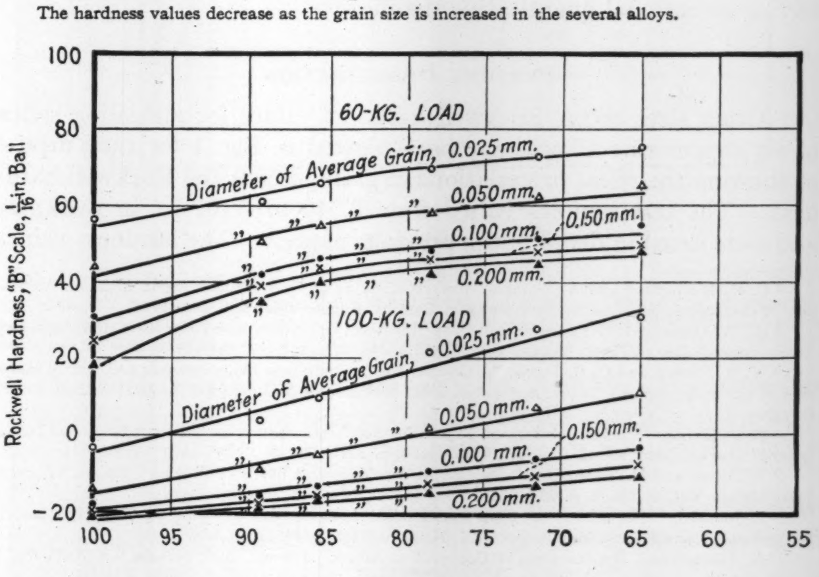

FIG. 2.—Effect of Grain Size on the Hardness of Six Copper-Zinc Alloys in the Annealed State.

For a given grain size the hardness values change progressively from that of pure copper to that of the alpha alloy of lowest copper content.

PREVIOUS INVESTIGATIONS

Mathewson and Phillips,[1] also Angus and Summers,[2] have shown that the greater the deformation suffered by a metal, the smaller are the crystals produced in a given time at a definite temperature (below 800° C.), and also the lower the recrystallization point. Brinell hardness indicates the grain size in annealed cartridge brass, as shown by Bassett and Davis.[3] An explanation of the hardness value maximum of the alpha range was given by Harris[4] who obtained so-called absolute hardness numbers for brasses from 100 to 50 per cent copper. He employed the Brinell instrument in testing hot forged samples which had been annealed at 650° C., but made no grain size measurements. He reported a maximum hardness at about 81 per cent copper. Several other investigators, among whom are Turner and Murray,[5] Johnson,[6] Meneghini,[7] and Bassett and Davis,[8] observed this maximum in the alpha phase at various points from 75 to 85 per cent copper. Malam[9] has shown the effect of cold working on hardness values of some copper alloys, but did not consider the grain size. He stated that Rockwell hardness numbers are quantitatively misleading and expressed regret for the use of tests which yield results having no rational quantitative significance.

PRESENT INVESTIGATION

Grain sizes *versus* Rockwell hardness values for annealing series of six copper-zinc alloys have been plotted in Fig. 1 for the purpose of showing the effect of variations in grain size on the Rockwell hardness. The test samples varied from 0.040 to 0.102 in. in thickness and were listed in detail in the previous paper.[10] The hardness values were determined with a Model 2K Rockwell hardness testing machine. The grain-size values are estimations obtained by direct comparison with a grain-size chart issued in 1929 by the Society's Committee E-4 on Metallography.[1] All tests were made on commercial products and slight variations from the values given would be expected.

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[1] C. H. Mathewson and A. Phillips, "Recrystallization of Cold Worked Alpha Brass on Annealing," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 54, p. 608 (1916).

[2] H. T. Angus and P. F. Summers, "The Effect of Grain Size upon Hardness and Annealing Temperature," *Journal*, Inst. Metals, Vol. XXXIII, No. 1, p. 115 (1925).

[3] W. H. Bassett and C. H. Davis, "A Comparison of Grain Size Measurements and Brinell Hardness of Cartridge Brass," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 60, p. 428 (1919).

[4] F. W. Harris, "Hardness of Brasses, Experiments on Measurement by Means of Strainless Indentation," *Journal*, Inst. Metals, Vol. XXVIII, No. 2, p. 327 (1922).

[5] T. Turner and M. T. Murray, "The Copper-Zinc Alloys: A Study of Volume Changes," *Journal*, Inst. Metals, Vol. II, No. 2, p. 98 (1909).

[6] F. Johnson, "The Alloys of Copper and Zinc: Investigation of Some of Their Mechanical Properties," *Journal*, Inst. Metals, Vol. XX, No. 2, p. 233 (1918).

[7] D. Meneghini, "The Hardness of Copper-Zinc Alloys," *Journal*, Inst. Metals, Vol. XIV, No. 2, p. 160 (1915).

[8] W. H. Bassett and C. H. Davis, "Physical Characteristics of Commercial Copper-Zinc Alloys," *Proceedings*, Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 55 (1928).

[9] J. E. Malam, "The Rockwell Hardness Test," *Journal*, Inst. Metals, Vol. 40, p. 375 (1928).

[10] C. H. Davis and E. L. Munson, "Hardness Relationships and Physical Properties of Some Copper Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 422 (1929).

It may be seen in Fig. 1 that the Rockwell hardness indicates the grain size of any given annealed alloy in the alpha phase of the copper-zinc system. As it has been demonstrated[10] that the tensile strength-hardness relationship of an annealing series of an alloy is a single line, it may be inferred, by analogy, that the tensile strength, scleroscope, and Brinell hardness also indicate grain size for any given annealed alloy.

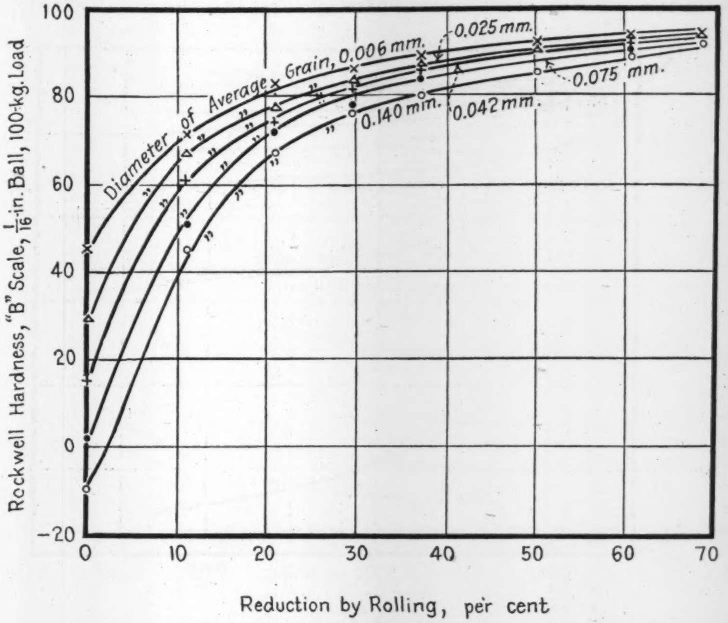

FIG. 3.—Effect of Grain Size on the Rockwell Hardness of 67–33 Copper-Zinc Alloys.

Annealed samples having 0.006, 0.025, 0.042, 0.075 and 0.140 mm. diameter of average grain were given reductions ranging from 10 to 68 per cent. A distinctly different set of hardness values is obtained for each grain size.

Figure 2 shows that for a given grain size there is a progressive change in the hardness values as the copper content is decreased. The values were obtained by interpolation from Fig. 1.

Hardness values alone do not reveal the grain size of an alloy which has been cold worked, but when used in conjunction with the amount of cold working they do indicate the grain size for a given alloy. On the other hand, if used with the grain size they indicate the amount of cold working for a given alloy. That is to say, if given the amount of cold work on an alloy, the original grain size may be learned by a hardness test. Conversely, knowing the grain size and hardness of a given alloy, the amount of cold working can be estimated.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 505 (1929).

It may be seen from the rolling series in Fig. 3 that for each grain size there is a distinctly separate set of hardness values, the rolling series on the finer-grained metal naturally having the greater hardness.

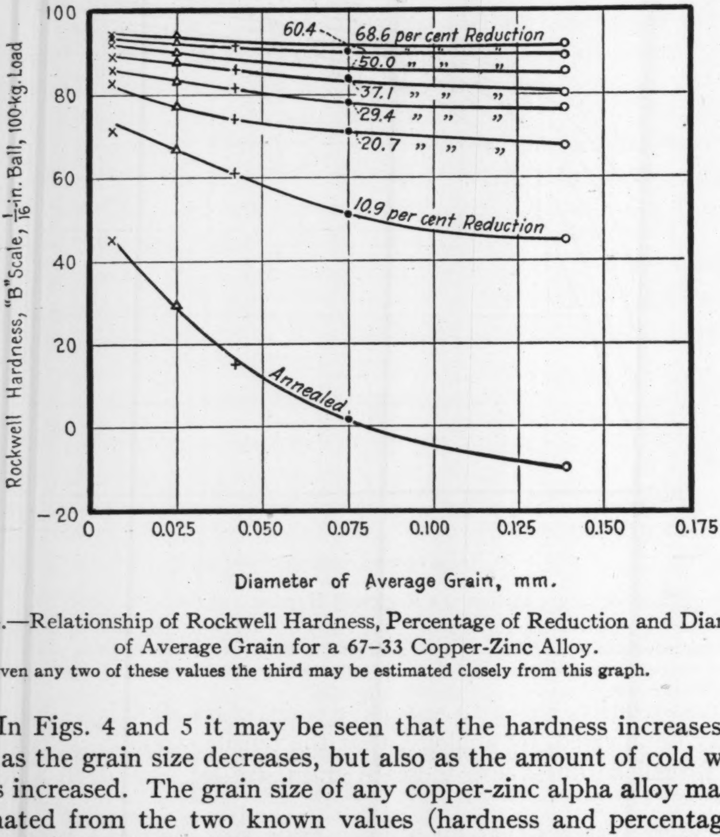

FIG. 4.—Relationship of Rockwell Hardness, Percentage of Reduction and Diameter of Average Grain for a 67–33 Copper-Zinc Alloy.

Given any two of these values the third may be estimated closely from this graph.

In Figs. 4 and 5 it may be seen that the hardness increases not only as the grain size decreases, but also as the amount of cold working is increased. The grain size of any copper-zinc alpha alloy may be estimated from the two known values (hardness and percentage of reduction) by direct reading on a chart; or if the hardness value and the grain size for a given alloy are known, the percentage of reduction may be determined from a graph.

The Rockwell hardness may be used with any of the copper-zinc alpha alloys to denote grain size for a given percentage of reduction. This may be accomplished by plotting a series of charts for each reduction. An example of such a chart for alloys reduced 20.7 per cent (two B. & S. numbers) is shown in Fig. 6.

A more complex composite chart, wherein several annealing and rolling series were plotted, would show the effect of grain size and cold working on the Rockwell hardness - tensile strength values of *all* the copper-zinc alpha alloys. Such a chart would also show that the Rockwell hardness - tensile strength relationship for a given grain size changes progressively with the decrease in copper content.

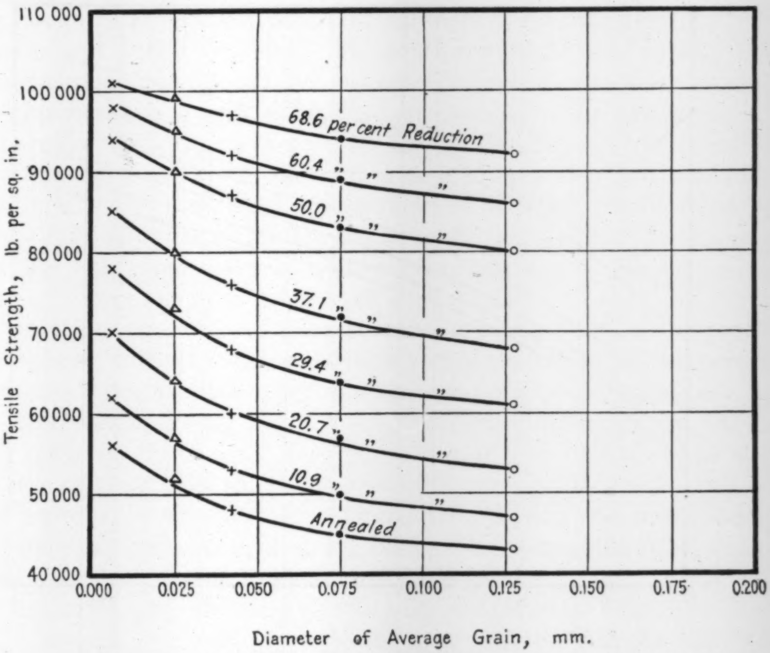

FIG. 5.—Relationship of Tensile Strength, Percentage of Reduction and Diameter of Average Grain for a 67–33 Copper-Zinc Alloy.

Given any two of these values the third may be estimated closely from the graph.

CONCLUSIONS AND SUMMARY

The principal conclusions to be drawn from this investigation are:

1. Hardness values indicate the grain size of any annealed alloy in the alpha phase of the copper-zinc series.

2. Hardness values alone do not indicate the grain size of a copper-zinc alloy which has been *cold worked.* If they are used in conjunction with the amount of cold working, the grain size is indi-

cated. Conversely, a known grain size together with hardness values indicates the amount of cold working.

3. If grain sizes are equal, the hardness values of the alpha copper-zinc alloys increase directly with the zinc content.

It is evident that the appearance of the hardness value maximum near the center of the alpha range of the copper-zinc alloys, which has

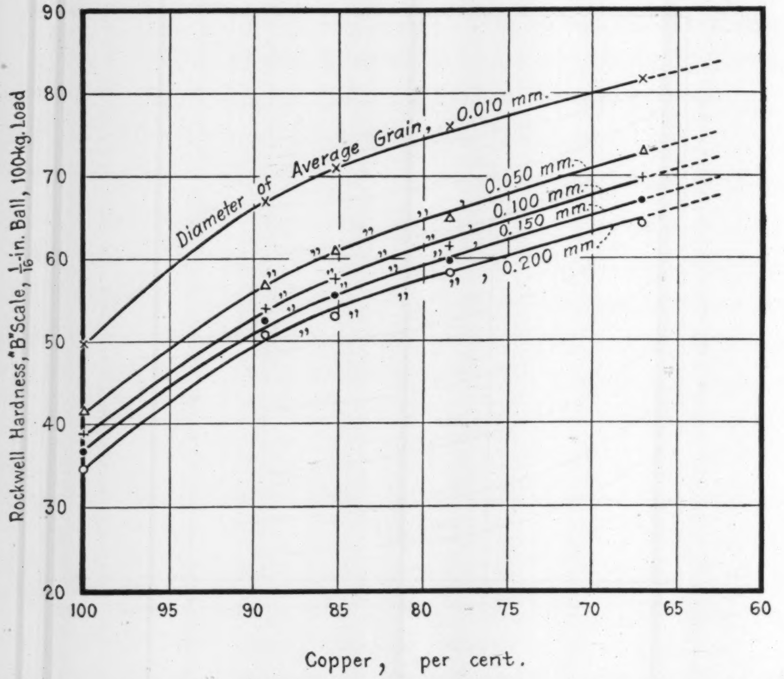

FIG. 6.—Copper and Four Copper-Zinc Alloys Annealed so as to Obtain 0.010, 0.050, 0.100, 0.150 and 0.200 mm. Diameter of Average Grain, Then Reduced 20.7 per cent by Rolling.

Hardness values for a given grain size change progressively from that of pure copper to that of the alpha alloy of lowest copper content.

been recorded by many investigators, is a function of the annealing temperature and the amount of previous cold working. If the temperature is so selected as to obtain the same grain size for all alloys, the hardness curve will have an even gradient rising slowly with the increase in zinc content.

It may be seen that the composition, grain size, and amount of cold working influence the physical properties to a considerable extent. The significance of the relationship of these three factors to the physical properties of the alpha copper-zinc alloys has been explained.

DISCUSSION

MESSRS. D. K. CRAMPTON[1] AND M. L. WOOD[1] (*presented in written form*).—The authors of this paper have succeeded in presenting a large amount of very valuable and intensely practical data in a very concise and usable manner. To our knowledge, data of this kind on the copper-zinc alloys have not heretofore been presented, and it is felt this paper is a very valuable contribution to the literature. It so happens that we have recently in our laboratory completed an investigation along very similar lines except that, whereas the authors investigated six alloys covering the range of 65 to 100 per cent copper, we used six alloys covering the range 63.77 to 73.43 per cent copper. In other words, our investigation was concentrated on the high brass portion only of the total range used by the authors.

In studying over our data in comparison with those presented in the paper, we find in many respects a very close check on properties determined, but in some other respects an appreciable discrepancy.

The accompanying Fig. 1 shows results obtained on six alloys, all of 0.060-in. thickness. This figure shows Rockwell hardness as a function of grain size, the grain sizes of course resulting from various temperatures of anneal. Two curves are shown, the upper being Rockwell hardness using a $\frac{1}{16}$-in. ball, 60-kg. load, and "B" scale, while the lower is for a $\frac{1}{16}$-in. ball, 100-kg. load, and "B" scale. Similar curves were obtained on 0.015-in. and 0.030-in. thickness. On all thicknesses we found precisely the same results: namely, that for all the alloys used a single smooth curve was obtained for the Rockwell hardness - grain size relationship, indicating that Rockwell hardness is a function of grain size and is entirely independent of copper content within the range used. This is contrary to the data presented in Figs. 1 and 2 of the paper and the authors' conclusions. We feel that the data presented in the paper are unquestionably correct for the higher copper contents, but we believe that from 65 to approximately 75 per cent copper the hardness should be constant for a given grain size.

The data upon which we base this discussion were very carefully obtained, and on each sample the grain size was actually counted in five different places, by two different men, using every precaution to get accurate and precise readings. The Rockwell hardness determinations were made with equal care and the machine itself frequently calibrated against standards.

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[1] Chase Cos., Inc., Waterbury, Conn.

The accompanying Fig. 2 shows curves similar to Fig. 1 except that the three thicknesses, 0.015, 0.030, and 0.060 in., are all presented in the case of the 60-kg. load, and both 0.030 and 0.060 in. in the case of the 100-kg. load. These curves are presented to indicate that the thickness of the metal, within the range used, has a decided effect on the Rockwell hardness - grain size relationship. This is contrary to the conclusion or inference in the paper, as the authors did not give actual thicknesses of sheets and seemed tacitly to assume that, within the range of gages they worked with, exact thickness was an unimportant factor.

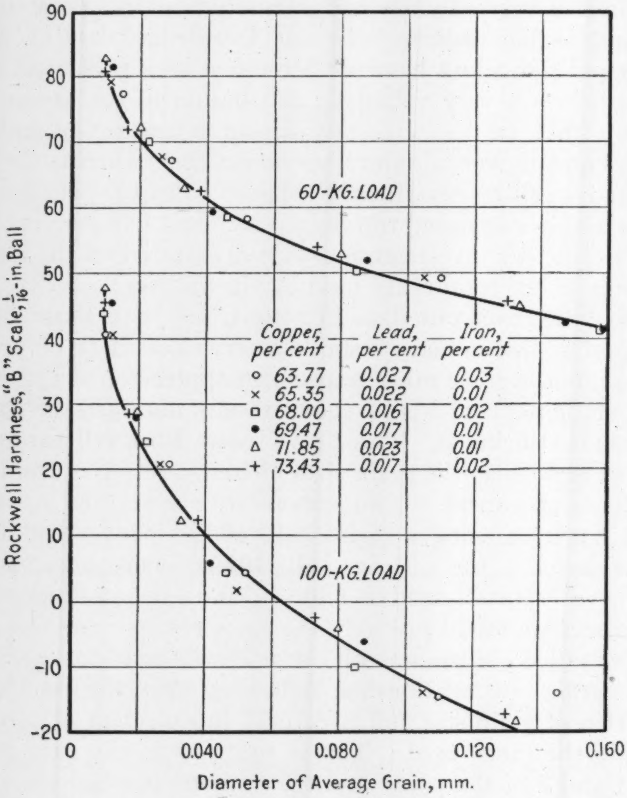

Fig. 1.—Effect of Grain Size on the Rockwell Hardness of High Brass, 0.060 in. Thick.

Curves similar to Figs. 1 and 2 were also obtained showing the relation between tensile strength and grain size, and elongation and grain size, and the same conclusions are drawn: namely that tensile strength and elongation are determined precisely by the grain size, and for a given grain size are entirely independent of the copper content within the limits 63.77 to 73.43 per cent.

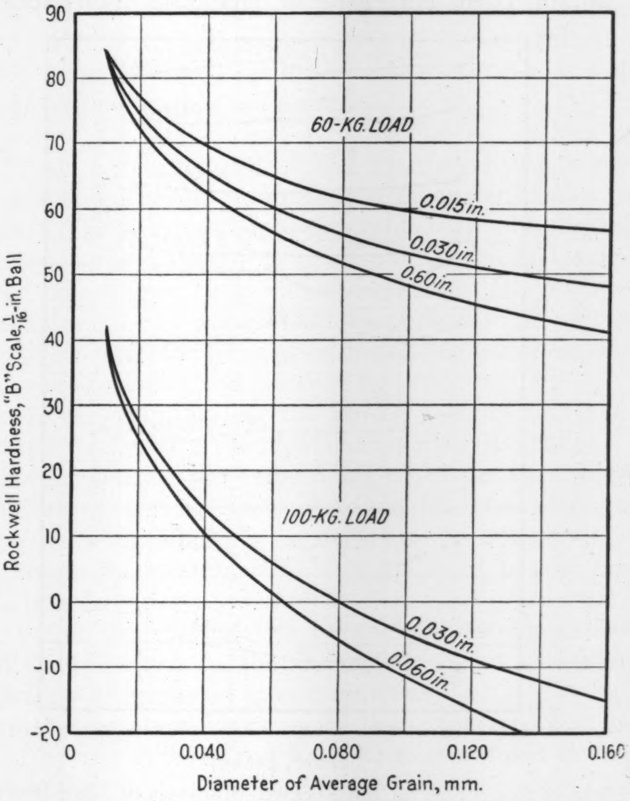

FIG. 2.—Comparison of Rockwell Hardness on Grain Size for Various Gages of High Brass.

The accompanying Fig. 3 is replotted from the data of Figs. 1 and 2 and should be compared directly with Fig. 2 of the paper for the range of copper content actually covered. Although the curves here given show some irregularity, it seems quite obvious that the general trend of all is a straight horizontal line indicating as stated above that Rockwell hardness is independent of the copper content within the range used, where the grain size is maintained constant.

In attempting to check up in detail the reasons for the discrepancies in the data here presented and those in the paper, we met with some difficulty, as all of the original measurements of the authors were not given. They referred to a previous paper by themselves[1] and stated that the material for the present paper was the same as that used in the previous one. Even on studying the previous paper, however, we still could not check in detail the discrepancies noted for various reasons. In the present paper they list an alloy of 65.04 per cent copper which was not used in the previous paper, and in the previous paper they have two alloys of 66.30 per cent copper and 67.13 per cent copper which were not used in the present paper. Further, in the previous paper Rockwell hardness readings for 60-kg. load were not given, nor were the grain sizes of the samples used.

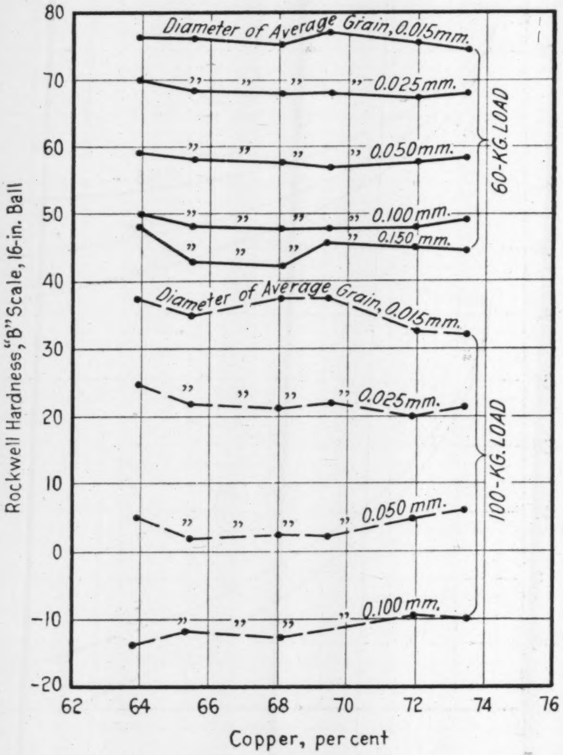

FIG. 3.—Effect of Grain Size on the Rockwell Hardness of High Brass, 0.060 in. Thick.

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[1] C. H. Davis and E. L. Munson, "Hardness Relationships and Physical Properties of Some Copper Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 422 (1929).

Also, exact thicknesses in all cases were not listed. It is unfortunate that the original data are not all available, as it is quite possible that if they were some of our present remarks might not be found relevant.

Even though it is impossible to check up in detail on the original data, we feel that the work reported in this discussion was carried out in sufficient detail and with sufficient precision to warrant the conclusion that within the range of copper content of approximately 64 to 73.5 per cent the authors' conclusions are not justified, and that within this range Rockwell hardness, tensile strength, and elongation are constant for a constant grain size.

MESSRS. C. H. DAVIS[1] AND E. L. MUNSON[1] (*authors' closure by letter*).—It will not be possible in the space available to review adequately the points brought up in the discussion by Messrs. Crampton and Wood. The authors purposely avoided the complicated area of the alpha-beta alloys except to point out the general agreement of the 65 per cent copper alloy with the others. The influence of the beta phase, though not always seen by means of the microscope, is very strong on both the grain growth and the hardness of annealed brasses in the range 63 to 68 per cent copper.

Even in carefully plotting the 100-kg. tests of Fig. 3 of the discussion there is found a decided composition difference. Messrs. Crampton and Wood's alloy containing 73.43 per cent copper is distinctly harder for a given grain size than the 71.85 per cent copper alloy, and both are similarly harder than the alloys still lower in copper, though the relation here is complicated by the nearness to the alpha-beta boundary.

There is an irregular relation between the 100-kg. and the 60-kg. Rockwell values given in the discussion. The values should be almost directly proportional to one another.

The other points brought up in the discussion have been fully recognized by the authors and have been considered in papers previously published by this Society.[2,3]

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[1] The American Brass Co., Waterbury, Conn.

[2] H. N. Van Deusen, L. I. Shaw and C. H. Davis, "Physical Properties and Methods of Test for Sheet Brass," *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part II, p. 173 (1927).

[3] J. R. Townsend, W. A. Straw and C. H. Davis, "Physical Properties and Methods of Test for Some Sheet Non-Ferrous Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 381 (1929).

SPECIMENS FOR TORSION TESTS OF METALS

BY R. L. TEMPLIN[1] AND R. L. MOORE[2]

SYNOPSIS

This paper describes tests made to determine the influence of form and size of specimen upon the results obtained in torsion tests. The merits of hollow cylindrical specimens, having different ratios of diameter to wall thickness and length to diameter as well as those of solid section have been investigated.

The results indicate that for determinations of shearing strength, the hollow specimen having a ratio of outside diameter to wall thickness, D/t, of from 12 to 14 and a ratio of length of thin-walled section to diameter, L/D, of about 0.5 is satisfactory. Specimens having a D/t ratio of about 10 are apparently best suited for elastic limit and yield point determinations. Comparative results from hollow and solid specimens show little variation in values of the modulus of elasticity in shear. Some data are given pertaining to the influence of specimen proportions upon values of shearing yield point obtained from autographic diagrams.

INTRODUCTION

As a part of the work of defining the shearing properties of wrought aluminum and its alloys, the authors have had occasion to investigate the merits of various forms and sizes of torsion test specimens. In view of the conspicuous lack of information in technical literature regarding the application of the torsion test and this phase of the problem in particular, comparative results from a number of specimen types are here presented. In offering these data to the Society their rather limited scope is appreciated, yet it is believed that they do form a basis from which more extensive and fruitful researches in this field of materials testing may be made.

Several types of torsion specimens have been proposed for determining the shearing properties of ductile metallic materials.[3] Except in cases where the modulus of elasticity in shear is to be obtained, the hollow thin-walled cylindrical specimen would appear to have very distinct advantages. Since the maximum shearing stresses in a specimen subject to torsion occur in the outer fibers, the stiffening effect of the relatively large amount of under-stressed material in solid specimens precludes their use for elastic limit and yield point determinations. The solid specimen is even more unsatisfactory for use in obtaining values of ultimate shearing strength since, in ductile materials, the uniform distribution of stress approached at the time of rupture invalidates the torsion formula for stress computation. In the case of the hollow specimen which fails by shear, however, the modulus of rupture is a reliable measure of shearing strength.

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[1] Chief Engineer of Tests, Aluminum Research Laboratories, Aluminum Company of America, New Kensington, Pa.

[2] Research Structural Engineer, Aluminum Research Laboratories, Aluminum Company of America, New Kensington, Pa.

[3] Proposed Methods for Torsion Tests to Determine the Mechanical Properties of Metallic Materials Under Shearing Stress, *Proceedings*, Am. Soc. Testing Mats., Vol. 25, Part I, p. 430 (1925).

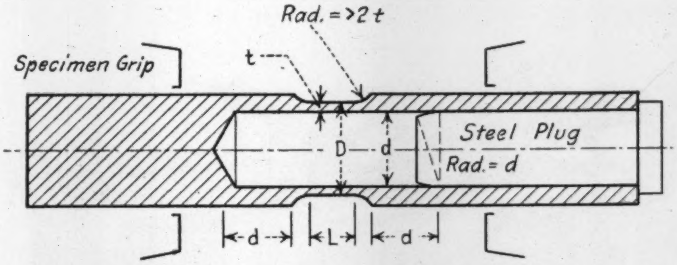

FIG. 1.—Torsion Test Specimen.

The problem of torsion specimen design resolves itself then into one of determining what limitations must be observed in the use of specimens of hollow section. In the tests herein described the influence of two variable elements has been considered; that is, the effect of the ratio of specimen outside diameter to wall thickness, D/t, and the ratio of the length of thin-walled section to diameter, L/D, on observed shearing properties.

TABLE I.—TENSILE PROPERTIES OF MATERIAL FOR TORSION SPECIMENS.

MATERIAL	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT
17ST Rod	61 600	37 000	25.0
17ST Tubing	61 900	41 000	31.0
51ST Rod	45 500	35 000	13.5
51SW Rod	38 000	20 000	31.0
51ST Bloom	41 000	33 000	13.0
2SH Tubing	21 600	20 000	12.5
2SH Rod	20 800	19 000	15.0
3SH Tubing	28 100	25 000	16.0

MATERIALS AND TEST METHODS

The materials used in this investigation include several forms and grades of wrought aluminum and aluminum alloys. The results of tensile tests on these materials are given in Table I.

Hollow specimens prepared from solid stock were machined so as to leave one gripping end solid. The boring and reaming operation, which extended approximately one-half diameter beyond the reduced section, was made with the same lathe set-up as was used for turning down the latter. Specimens from tubing were turned in the lathe, on centers, in order to insure as near as possible reduced sections of uniform wall thickness.

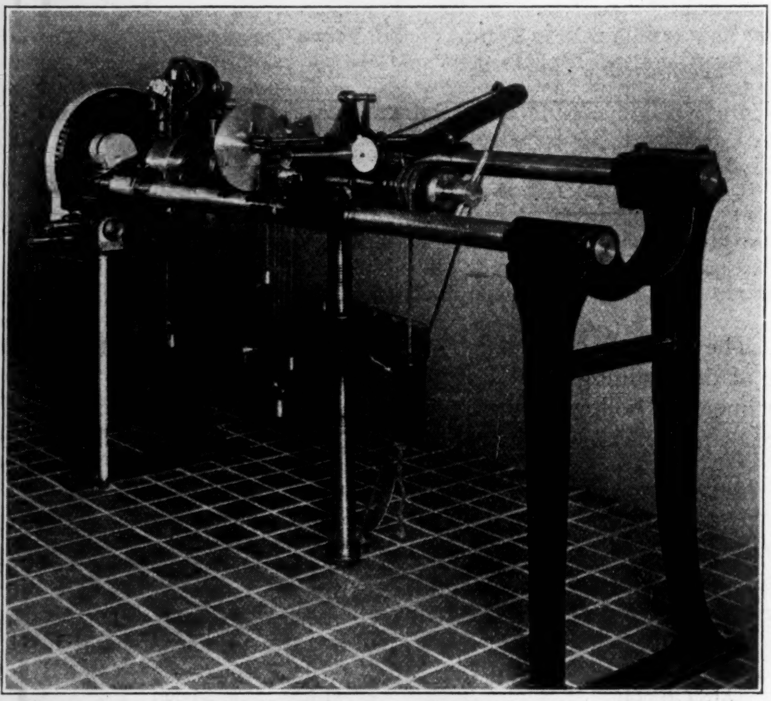

FIG. 2.—Torsion Testing Machine.

The sketch, Fig. 1, indicates the general form of specimen used and is explanatory of the nature of the design variables considered.

All tests were made in the Amsler torsion machine shown in Fig. 2. It has a range of four different capacities: 240, 400, 800 and 1200 ft-lb., with corresponding indicated sensitivities of $\frac{1}{2}$, 1, 1, and 5 ft-lb., respectively. The machine is equipped with V-notched specimen grips, an autographic recorder, and both manual and motor drive facilities, the latter operating the turning head at approximately 0.36 r.p.m.

The Martens mirror apparatus was used in obtaining torsional stress-strain data. The sensitivity of this instrument is ±0.00005 radians.

Values of all shearing stresses and moduli of rupture were computed by means of the torsion formula for circular sections:

$$S = \frac{Tr}{J}$$

where S is the shearing stress, T the twisting moment, r the radius, and J the polar moment of inertia.

TABLE II.—EFFECT OF VARIATIONS IN RATIO OF DIAMETER TO THICKNESS, D/t, ON MODULUS OF RUPTURE.

MATERIAL	RATIO, OUTSIDE DIAMETER TO WALL THICKNESS, D/t	RATIO, LENGTH OF THIN-WALLED SECTION TO DIAMETER, L/D	MODULUS OF RUPTURE, LB. PER SQ. IN.	TYPE OF FAILURE
17ST (Rod)	2	0.5	56 800	Shear
	7	0.5	47 700	Shear
	11	0.5	44 300	Shear
	16	0.5	44 000	Shear
	34	0.5	38 200	Collapse
17ST (Tubing)	6	0.5	47 000	Shear
	8	0.5	45 700	Shear
	10	0.5	44 900	Shear
	14	0.5	44 700	Shear
	18	0.5	44 200	Shear
51SW (Rod)	2	0.5	36 100	Shear
	7	0.5	31 300	Shear
	11	0.5	29 700	Shear
	16	0.5	29 000	Shear
	34	0.5	24 800	Collapse
51ST (Rod)	2	0.5	41 300	Shear
	8	0.5	35 100	Shear
	16	0.5	33 800	Shear

Values of shearing yield point have been determined from autographic diagrams and from plotted torque-twist curves. In the former case the point of deviation from a straight line has been taken as the yield point, while on the plotted curves an arbitrary value has been taken as the stress at which the permanent detrusion equals 0.2 per cent, assuming such permanent set may be measured by the departure of the curve from the modulus line extended. This criterion for determining shearing yield point is analogous to the method commonly used in obtaining yield point in tension, and gives values

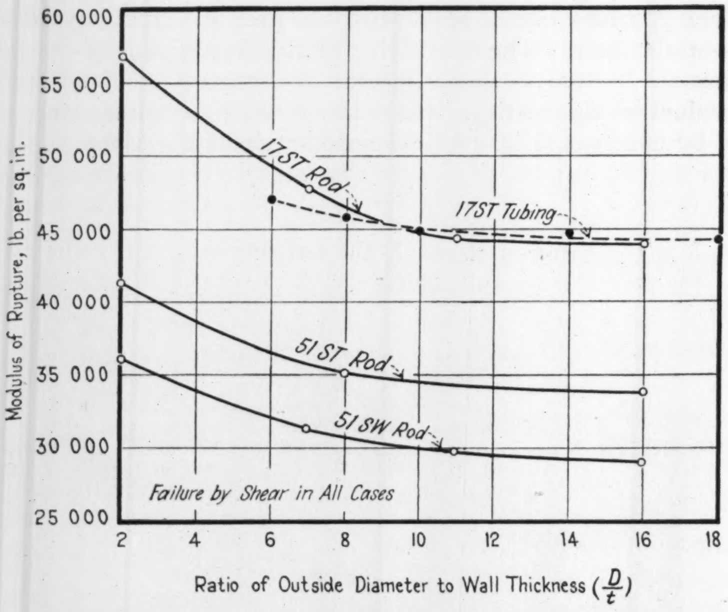

FIG. 3.—Showing Relation Between Ratio of Diameter to Wall Thickness, D/t, and Modulus of Rupture. Ratio of length of thin-walled section to diameter, L/D, 0.5 constant.

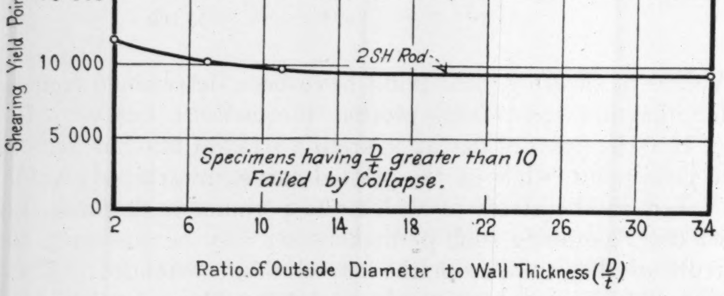

FIG. 4.—Showing Relation Between Ratio of Diameter to Wall Thickness, D/t, and Yield Point in Shear.

which bear approximately the same relation to shearing strengths as do yield points in tension to tensile strengths.

RESULTS AND DISCUSSION

The effect of variations in D/t ratio on modulus of rupture in torsion is indicated by the results given in Table II. The data obtained from specimens failing by shear are plotted in Fig. 3.

While, theoretically, the thinnest-walled specimen to fail in shear is the one best suited for determining shearing strength, little advantage is apparently to be had by using a D/t ratio greater than from 12 to 14. The increased possibility of errors in measurement using thinner walled specimens probably counteracts what other merits they may possess.

TABLE III.—EFFECT OF VARIATIONS IN RATIO OF DIAMETER TO THICKNESS, D/t, ON YIELD POINT IN SHEAR.[a]

MATERIAL	RATIO, OUTSIDE DIAMETER TO WALL THICKNESS, D/t	YIELD POINT, LB. PER SQ. IN.	TYPE OF FAILURE
17ST (Rod)	2	28 000	Shear
	7	26 400	Shear
	11	25 500	Collapse
	34	24 100	Collapse
17ST (Tubing)	6	23 200	Shear
	10	22 000	Shear
	14	21 600	Collapse
2SH (Rod)	2	11 700	Shear
	7	10 200	Shear
	11	9 700	Collapse
	34	9 400	Collapse
51ST (Rod)	2	24 700	Shear
	16	21 300	Collapse
51ST (Bloom)	2	23 700	Shear
	9	20 600	Shear
	18	19 100	Collapse

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[a] Yield points obtained from plotted torque-twist curves.

It is interesting to note that the curves in Fig. 3 approach a lower limit of stress equal to approximately 0.8 of the modulus of rupture obtained from the solid specimens in each group, or those having a D/t ratio of 2. A value of shearing stress equal to 0.75 of the modulus of rupture of a solid specimen would indicate a uniform distribution of stress over the latter, a condition which apparently is only approximated in the materials tested.

Table III gives the results of tests to determine the effect of variations in *D/t* ratio on yield point in shear. The latter were all taken from plotted torque-twist curves according to the arbitrary procedure already described.

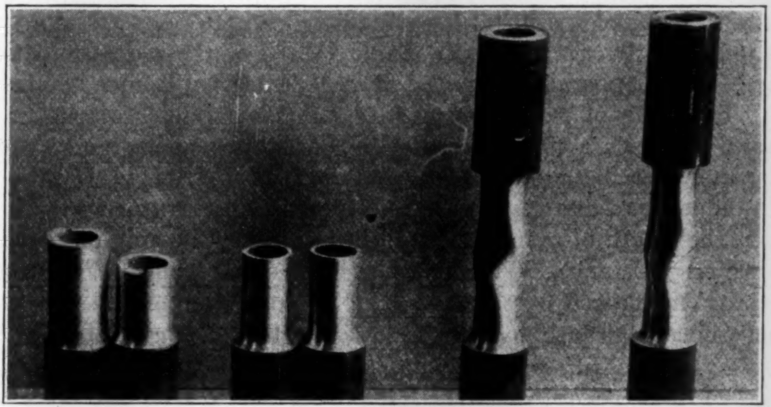
TABLE IV.—EFFECT OF VARIATIONS IN RATIO OF DIAMETER TO THICKNESS, *D/t*, ON MODULUS OF ELASTICITY IN SHEAR.

MATERIAL	RATIO, OUTSIDE DIAMETER TO WALL THICKNESS, *D/t*	MODULUS OF ELASTICITY IN SHEAR, LB. PER SQ. IN.
17ST (Rod)	2	3 925 000
	7	3 975 000
	11	3 975 000
17ST (Tubing)	6	3 790 000
	10	3 840 000
	14	3 790 000
51ST (Rod)	2	3 700 000
	16	3 650 000
2SH (Rod)	2	3 650 000
	7	3 675 000
	11	3 600 000

TABLE V.—EFFECT OF VARIATIONS IN RATIO OF LENGTH TO DIAMETER, *L/D*, ON MODULUS OF RUPTURE.

MATERIAL	RATIO, LENGTH OF THIN-WALLED SECTION TO DIAMETER, *L/D*	RATIO, OUTSIDE DIAMETER TO WALL THICKNESS, *D/t*	MODULUS OF RUPTURE, LB. PER SQ. IN	TYPE OF FAILURE
17ST (Rod and Tubing)	0.5	6	47 000	Shear
	3.0	6	47 500	Shear
	0.2	10	45 300	Shear
	0.5	10	44 900	Shear
	1.0	10	44 300	Shear
	3.0	10	44 900	Shear
	6.0	10	44 000	Collapse
	0.5	14	44 700	Shear
	3.0	14	40 800	Collapse
	0.5	18	44 200	Shear
	1.0	18	42 400	Collapse
	3.0	18	35 100	Collapse
	0.5	34	38 200	Collapse
	3.0	34	28 600	Collapse

From Fig. 4 it appears that the supporting action of the understressed material in the solid specimens is a slightly more significant factor than the tendency toward compressive collapse in the hollow types. Specimens having a *D/t* ratio of approximately 10, being on the dividing line of failure by shear and collapse, would seem to be satisfactory for determinations of shearing yield points. It will be noted that the values obtained from these specimens are from 0.85 to 0.9 of those determined from tests on the solid specimens. This relation between the shearing yield points from hollow and solid torsion specimens has also been found by investigators using ductile steels.[1]



6	10	14	18

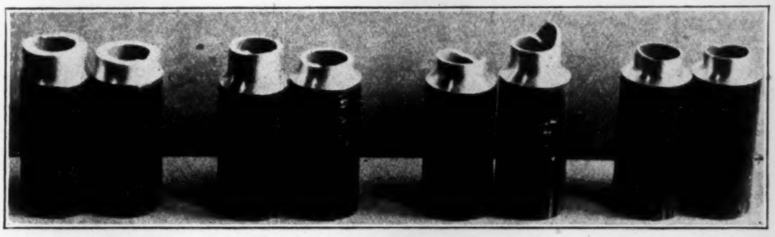
Ratio, Outside Diameter to Wall Thickness, D/t.

3	3	3	3

Ratio, Length of Thin-Walled Section to Diameter, L/D.

47 500	44 900	42 400	35 100

Modulus of Rupture, lb. per sq. in.



6	10	14	18

Ratio, Outside Diameter to Wall Thickness, D/t.

0.5	0.5	0.5	0.5

Ratio, Length of Thin-Walled Section to Diameter, L/D.

47 000	44 900	44 700	44 200

Modulus of Rupture, lb. per sq. in.

FIG. 5.—Showing Test Specimens That Have Failed in Torsion.

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[1] F. B. Seely and W. J. Putnam, "The Relation Between the Elastic Strengths of Steel in Tension, Compression and Shear," *Bulletin No. 115*, Engineering Experiment Station, University of Illinois, Urbana, Ill.

While the solid torsion specimen is usually recommended for determinations of modulus of elasticity in shear, the hollow specimen, within certain limits, would appear to be equally satisfactory. Tests on both types of specimens have indicated this to be essentially true, as indicated by the results in Table IV. For these determinations the Martens apparatus was used on gage lengths of from 2 to 4 in.

The effect of variations in *L/D* ratio on modulus of rupture is shown by the data given in Table V. For specimens having a ratio of diameter to wall thickness of 10 or less, variations in *L/D* ratio do not influence results appreciably. For thinner-walled specimens, however, the length of reduced section has a decided bearing on ultimate torsional resistance. This relation between *D/t* and *L/D* ratios is clearly emphasized by the moduli of rupture obtained on the specimens illustrated in Fig. 5.

TABLE VI.—EFFECT OF VARIATIONS IN RATIO OF LENGTH TO DIAMETER, *L/D*, ON YIELD POINT IN SHEAR.[a]

MATERIAL	RATIO, LENGTH OF THIN-WALLED SECTION TO DIAMETER, *L/D*	RATIO, OUTSIDE DIAMETER TO WALL THICKNESS, *D/t*	YIELD POINT, LB. PER SQ. IN.
17ST (Tubing)	0.2	10	23 300
	0.5	10	22 000
	1.0	10	20 500
	3.0	10	20 500
	6.0	10	16 500
17ST (Rod)	1	2	24 100
	20	2	20 900
2SH (Tubing)	1.5	9	10 000
	4	9	9 500
	13	9	8 800
3SH (Tubing)	1	12	11 600
	4	12	10 500
	11	12	10 300
	22	12	9 500

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[a] Yield points obtained from autographic diagrams.

In determinations of shearing yield point by means of autographic recorders, specimen form and size may be of more significance than is readily appreciated. The results given in Table VI show the effect of variations in *L/D* ratio on this property. The lower yield point results on the longer specimens are attributed principally to the greater multiplication obtained on the autographic recorder by their use. Speed of testing may be an appreciable factor on the shorter specimens, however, since it varies inversely as the length for a given specimen diameter and speed of rotation of the twisting head. One conclusion is obvious from the results given, that is the importance of using specimens of geometrically similar form for comparative tests.

While few data have been included in this paper regarding autographic yield points from specimens of small *L*/*D* ratio, from other observations it appears that values so obtained agree quite closely with the yield points taken from plotted stress-strain curves. Further study may reveal the adaptability of one form of specimen for both yield point and ultimate strength determinations.

CONCLUSION

In conclusion, the authors are of the opinion that the development of torsion testing offers a very profitable field for further study. The increasing demand for accurate information regarding the shearing properties of structural materials emphasizes the need for a definite form of specimen and method of test. While certain fundamentals in specimen design have been emphasized by the results given in this paper, a more extensive use of the test must be made before definite recommendations can be outlined.

DISCUSSION

MR. F. B. SEELY[1] (*presented in written form*).—The paper by Messrs. Templin and Moore presents material that should be very useful in indicating a satisfactory test procedure and form of specimen for determining the shear properties of metals—a field in which but little work has been done.

The authors have done well to point out limitations to the use of specimens having a very thin wall and a long turned-down section in comparison with the diameter of the specimen. If the shearing elastic strength (the authors' yield point) of the material is found from a stress-strain diagram obtained from a specimen with a relatively thin wall and a relatively long turned-down section, the value obtained may not be a stress corresponding to a slight *plastic yielding* of the material, for the reason that the curvature (deviation from a straight line) in the stress-strain diagram may begin because of *elastic buckling* of the thin walls before the yield point of the material is reached. Thus the failure of a thin-walled specimen may be similar to the failure of a very slender column, and not a failure due to yielding of the material. Further, since resistance to elastic buckling depends on the stiffness of the material, that is, on the modulus of elasticity, it would be expected that the minimum satisfactory wall thickness for specimens of steel could be smaller than for specimens of aluminum or brass of the same diameter and length of turned-down section.

Likewise, in determining a value of the shearing modulus of elasticity of steel a longer gage length is needed than for aluminum, in order to obtain the same degree of precision in the measured angles of twist, assuming the same instruments to be used. The limiting relative dimensions of a satisfactory torsion specimen are, therefore, not the same for all metals.

The test results on aluminum reported in this paper together with those on steel reported in *Bulletin No. 115* of the Engineering Experiment Station of the University of Illinois make it seem clear that a reliable, although approximate, value of the shearing elastic strength of a ductile metal can be found from a test of a *solid* torsion specimen; the shearing elastic strength of the material being 0.85

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of the elastic strength obtained from the test results of the solid specimen. This fact may prove to be of considerable importance.

MR. L. B. TUCKERMAN.[1]—It is a comfort to see that some people are actively engaged in studying the question of the effect of the design of test specimens upon test results. Mr. Templin has, as we all know, spent much energy and time upon this problem. There is only one question I would like to raise: the use of the words "modulus of rupture" in connection with torsion specimens seems to me inadvisable. "Modulus of rupture" as a conventional term for a nominal stress computed in an altogether fictive manner in a bend test is well established. To use the expression "modulus of rupture" for another nominal stress computed in another fictive manner on a torsion specimen seems to me likely to lead to misconception. I should like to suggest that some other term be devised to fit this particular purpose.

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ELASTIC BEHAVIOR OF SPRING MATERIALS

M. F. SAYRE[1]

SYNOPSIS

This paper reports the results of tests on spring steels and phosphor bronze, and also on hard-drawn aluminum alloy wire. These tests indicate that the elastic limit and the proportional limit do not coincide, and that the true stress-strain line aside from any plastic flow or hysteresis effects, is curved throughout. Definite quantitative values for the rate of change of modulus of elasticity with stress intensity are given. Figures are also given which indicate, for certain steel specimens, a marked increase in hysteresis and decrease in modulus of elasticity as a result of temporary overstressing beyond the elastic limit.

INTRODUCTION

For the past two and one-half years, problems in elastic behavior have been under investigation at Union College as part of a program of spring research, sponsored by the Research Committee on Mechanical Springs of the American Society of Mechanical Engineers, under J. K. Wood as chairman. The investigation started as a study of the properties of spring steel in bending, with particular reference first to hysteresis and second to the effect of over-stressing, as in the cold coiling of springs, upon future behavior. Special methods and special apparatus were devised for this study. This work was paralleled by studies of properties in tension, and it soon became apparent that some of the anomalies in the results of the bending tests were associated with peculiarities in tensional behavior, and could be best studied by means of measurements made in tension. Additional attention was therefore directed to this phase of the work. The results have been reported in papers presented before the American Society of Mechanical Engineers in December, 1928,[2] and in December, 1929,[3] but some phases of this work as already reported, and also certain results obtained since the publication of the last mentioned paper, are of such nature that they may be of interest to members of the American Society for Testing Materials. This will particularly apply to certain investigations of elastic and proportional limits and of elastic behavior above and below the elastic limit.

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[1] Associate Professor of Mechanical Engineering, Union College, Schenectady, N. Y.

[2] M. F. Sayre and Anthony Headley, "Stress Distribution and Hysteresis Losses in Springs," *Transactions*, Am. Soc. Mechanical Engrs., Applied Mechanics Division, Vol. 51, p. 287 (1928).

[3] M. F. Sayre, "Elastic and Inelastic Behavior in Spring Materials," *Mechanical Engineering*, December, 1929, p. 915.

METHODS OF TESTING

Three series of investigations have been carried on using different methods. In the first series, tests were made on specimens of flat heat-treated steel wire, 0.68 per cent carbon, $\frac{1}{8}$ by $\frac{1}{2}$ in. in cross-section. An Amsler testing machine was used and a mirror extensometer of the Riehle-Sayre type, developed by the author.[1] One scale division on this extensometer represents an elongation of 1 part in 100,000. The stress-strain lines so obtained showed a slight curvature but an attempt was made to fit successive straight lines to them, thus securing an upper and a lower proportional limit and two different moduli of elasticity, and they were so described in the report issued in 1928.[2]

During the second series of tests it was endeavored to raise the precision of the work to the highest possible extent, in order to obtain definite quantitative, rather than qualitative, results in measurements of modulus of elasticity changes and of elastic hysteresis. For this reason, the gage length of the extensometer was increased from 2 to 8 in., and the scale position was modified, so that each of the 500 divisions on the scale represented an elongation of 1 part in 500,000. Full scale range corresponded to 1 part in 1,000, or a load range (for steel specimens) of 28,000 to 30,000 lb. per sq. in. The calibration of the extensometer was checked by direct measurements on its lever system, and the testing machine was calibrated by standard dead weights to a total load of 4,000 lb. A new Amsler machine was used, located in a large ground floor room, practically free from vibration. The temperature of the room remained relatively uniform during any one test, but temperatures were taken and corrections made when necessary. A cloth curtain around the specimen and extensometer shielded them from direct drafts.

Two different objectives were aimed at during this second series of tests, first, a study of the effect of different stress ranges upon the amount of elastic hysteresis in tension and, second, an accurate determination of modulus of elasticity and of its changes under varying stresses both below and above the elastic limit. In studying hysteresis, the specimen was put through a series of cycles of loading and unloading between a nominal load and the desired maximum load in tension. After the specimen had approached a cyclical state, sets of readings were taken with the extensometer for three complete cycles or more if necessary to obtain consistent values. The elongation range of the extensometer was such that it was not possible to obtain elongation readings over the full height of the stress-strain curves. For this reason, the extensometer was set at zero at a load slightly below the mid-point of the full load range and then readings taken at five loads within the range of the extensometer on the ascending side of the hysteresis loop and repeated at the same loads on the descending side of the loop. In this way, the width of the loop as measured by the differences in readings ascending and descending was taken at five points near the middle of the loop. The sides of the loop are so

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[1] M. F. Sayre, "A New Type of Mirror Extensometer," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 660 (1926).

[2] *Transactions*, Am. Soc. Mechanical Engrs., Applied Mechanics Division, Vol. 51, p. 287 (1928).

TABLE I.—MEAN WIDTH OF HYSTERESIS LOOPS IN TENSION TESTS.

0.68 per cent carbon heat-treated flat steel wire, $\frac{1}{8}$ by $\frac{1}{2}$ in.

Maximum Stress, lb. per sq. in.	Width of Loop, in. per inch			
	Bar No. 17	Bar No. 22	Bar No. 28	Mean
FIRST SERIES				
53 590	0.0000044	0	0	0
80 390	0.0000016	0	0.0000012	0.0000009
107 180	0.0000108	0.0000064	0.0000040	0.0000071
133 980	0.0000124	0.0000124	0.0000032	0.0000093
147 380	0.0000148	0.0000124	0.0000092	0.0000121
160 780	0.0000252	0.0000152	0.0000196	0.0000200
167 480	0.0000464	0.0000616	0.0000300	0.0000460
174 180	0.0001264	0.0000564	0.0001000	0.0000943
SECOND SERIES, AFTER LOADING TO 174 000 LB. PER SQ. IN.				
53 590	0.0000036	....	0.0000016	0.0000026
80 390	0.0000124	0.0000100	0.0000052	0.0000092
107 180	0.0000176	0.0000164	0.0000092	0.0000144
133 980	0.0000272	0.0000352	0.0000212	0.0000279
147 380	....	0.0000408	....	0.0000408
160 780	0.0000560	0.0000528	0.0000360	0.0000483
167 480	....	0.0000628	....	0.0000628
174 180	0.0001140	0.0000932	0.0000688	0.0000920
180 870	0.0002800	0.0001892	0.0001820	0.0002171
THIRD SERIES, AFTER LOADING TO 181 000 LB. PER SQ. IN.				
53 590	0.0000068	0.0000068	0.0000088	0.0000075
80 390	0.0000140	0.0000184	0.0000144	0.0000156
107 180	0.0000308	0.0000320	0.0000248	0.0000292
133 980	0.0000516	0.0000596	0.0000408	0.0000507
160 780	0.0000988	0.0001332	0.0000804	0.0001041
174 180	0.0001420	0.0001508	0.0001200	0.0001376
FOURTH SERIES, AFTER TWO WEEKS REST				
53 590	0	0.0000076	....	0.0000038
80 390	0.0000124	0.0000160	....	0.0000142
107 180	0.0000228	0.0000292	....	0.0000260
133 980	0.0000472	0.0000596	....	0.0000534
147 380	0.0000680	0.0000748	....	0.0000714
160 780	0.0000904	0.0001068	....	0.0000986
167 480	0.0001024	0.0001240	....	0.0001132
174 180	0.0001252	0.0001324	....	0.0001288

nearly straight and parallel at this point that the average of these five differences or rather the mean of three sets of five differences each could be taken as the width of the loop itself. The results of such sets of readings are given in Table I and are shown graphically in Fig. 6.

The obvious method of studying modulus of elasticity variations was to take measurements over the complete stress-strain curve itself from zero load to the yield point. This from a practical point of view, was not feasible, due to the limited stress range of the extensometer without resetting; and it was also undesirable from a theoretical point of view, since it brought into play the factor of elastic hysteresis and also made it impossible to study the elastic elongation of the bar as distinguished from the effect of minute plastic yield which might be simultaneously occurring.

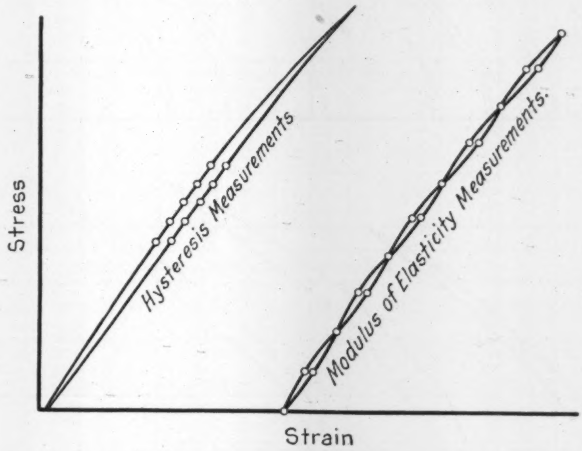

FIG. 1.—Routine with Mirror Extensometer.

To avoid these effects, the total curve was broken up into a series of sections each short enough so that the elastic hysteresis within that range would be small. Starting with the lowest of these sections, the specimen was placed in cyclical or nearly cyclical state by successive loading and unloading within this range. Most or all of the plastic yield occurred during this period. The extensometer was then set at zero at the lower end of the range and readings were taken at the two ends of the range on ascending and descending loads for at least three cycles. After the specimen had been placed in cyclical condition for the next higher section by successive loadings and unloadings, the extensometer was loosened and reset at an 8-in. gage length and at zero reading for the lower end of the new load section. Readings of elongation over this range were now taken for at least three cycles. This routine was repeated for each successive section. In this way, instead of obtaining the stress-strain curve for the specimen with ascending and descending loads as a single loop, it was obtained as a series of small loops, touching each other at their tips, as shown in Fig. 1. Successive loops represented identical stress ranges, and practically the full scale range of the extensometer, starting at zero, was used for each small loop.

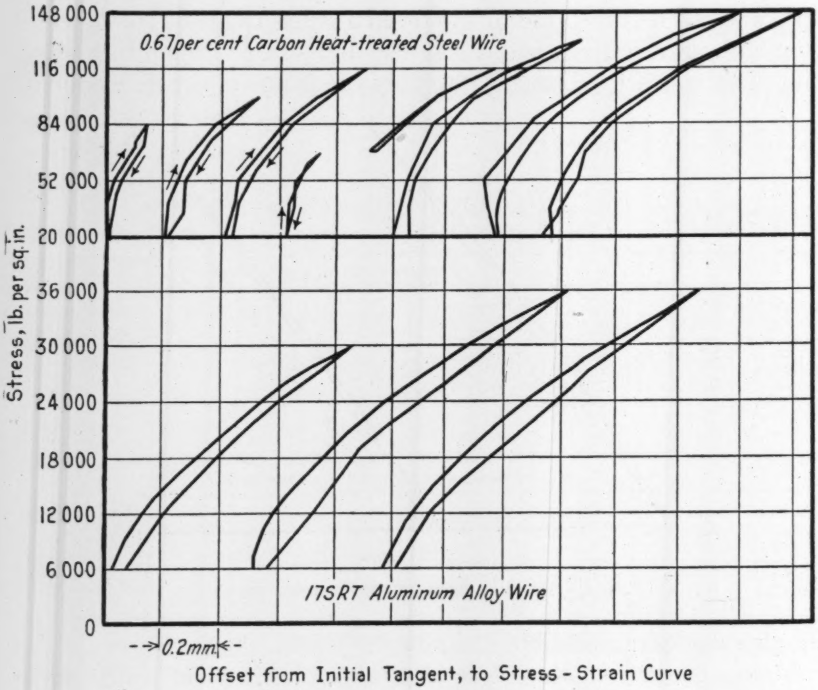

FIG. 2.—Typical Hysteresis Loops.

This routine had the additional advantage that comparison could be made between the elastic elongation resulting from a given stress range, first with a low average stress, and then with progressively higher average stresses, in each case the elongation being measured over virtually the same portion of the extensometer scale. In this way, the effect of errors in graduation and calibration of the extensometer were eliminated from comparative values of modulus of elasticity at various stresses, although, of course, the absolute value was still affected.

TABLE II.—EFFECT OF OVERSTRAIN UPON MODULUS OF ELASTICITY.[a]

0.68 per cent carbon heat-treated flat steel wire, $\frac{1}{8}$ by $\frac{1}{2}$ in.
Amsler testing machine.
Riehle-Sayre extensometer, modified.
Gage length 8 in.
Temperature 74 to 78° F.

Stress Range, lb. per sq. in.	Temperature		Unit Strain, Bar No. 111, p.p.m.			Modulus of Elasticity, lb. per sq. in.		
	deg. Cent.	deg. Fahr.	As Read	Corrected for Temperature	Corrected for Elongation	Bar No. 111	Bar No. 112	Bar No. 113
MEAN, FIRST TO FIFTH SERIES								
1 600 to 27 000....	24.4	76	907.2	906.2	906.2	29 580 000	30 330 000	29 370 000
27 000 to 54 000....	24.4	76	914.6	913.6	913.6	29 340 000	29 540 000	29 170 000
54 000 to 80 500....	24.4	76	920.0	919.0	919.0	29 170 000	29 470 000	29 010 000
80 500 to 107 500....	24.7	76.5	935.6	924.6	924.6	29 000 000	29 190 000	28 710 000
107 500 to 134 000....	25.2	77.3	929.8	928.6	928.6	28 870 000	29 540 000	28 450 000
134 000 to 161 000....	24.5	76.2	942.0	941.0	941.0	28 500 000	29 250 000	28 230 000
SIXTH SERIES, AFTER LOADING TO 174 500 LB. PER SQ. IN.								
1 600 to 27 000....	23.3	74	917.0	916.2	914.8	29 300 000	29 630 000	
27 000 to 54 000....	23.6	74.5	916.0	915.2	913.8	29 330 000	29 320 000	
54 000 to 80 500....	23.6	74.5	916.6	915.8	914.2	29 310 000	29 100 000	
80 500 to 107 500....	23.9	75	927.6	926.8	925.4	28 960 000	28 950 000	
107 500 to 134 000....	23.9	75	941.6	940.8	939.4	28 530 000	28 830 000	
134 000 to 161 000....	24.2	75.5	940.0	939.0	937.6	28 590 000	28 630 000	
147 500 to 174 500....	24.2	75.5	946.6	945.6	944.2	28 380 000	28 520 000	
154 500 to 181 000....	24.4	76	978.6	977.6	972.4	27 570 000	28 460 000	
SEVENTH SERIES, AFTER LOADING TO 181 000 LB. PER SQ. IN.								
1 600 to 27 000....	25.6	78	937.6	936.2	931.0	28 790 000	28 970 000	
27 000 to 54 000....	25.6	78	944.0	942.6	937.4	28 590 000	28 960 000	
54 000 to 80 500....	25.6	78	939.0	937.6	932.4	28 740 000	28 910 000	
80 500 to 107 500....	25.6	78	946.6	945.2	940.0	28 510 000	28 790 000	
107 500 to 134 000....	25.6	78	956.0	954.6	949.4	28 230 000	28 630 000	
134 000 to 161 000....	25.6	78	949.0	947.6	942.4	28 440 000	28 340 000	
154 500 to 181 000....	....	....	.....	.....	.....	....	28 200 000	
158 000 to 184 500....	....	....	.....	.....	.....	....	28 030 000	

[a] In order to reduce hysteresis and creep effects, these readings were taken as a series of successive closed loops, in approximately cyclic condition. Each figure represents an average of several runs on a given loop. The extensometer was reset at zero before each run.

TABLE III.—MODULUS OF ELASTICITY OF $3\frac{1}{2}$-PER-CENT NICKEL STEEL.

0.500 in. in diameter; threaded ends.

Stress Range, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.						
	Bar No. 530		Bar No. 538		Bar No. 476		Mean
	Up	Down	Up	Down	Run No. 1	Run No. 2	
1 000 to 21 000..................	29.04	29.06	29.04	29.08	.....	.....	29.06
20 000 to 40 000..................	28.98	29.02	29.04	29.08	.....	.....	29.03
40 000 to 60 000..................	28.86	28.89	28.95	28.99	.....	.....	28.92
60 000 to 80 000..................	28.80	28.88	28.87	28.92	.....	.....	28.87
68 000 to 88 000..................	28.70	28.78	28.74	28.78	.....	.....	28.77
800 to 24 000..................	.....	.....	.....	.....	28.79	28.85	28.82
12 000 to 36 000..................	.....	.....	.....	.....	28.68	28.43	28.55
24 000 to 48 000..................	.....	.....	.....	.....	28.54	28.53	28.53
36 000 to 60 000..................	.....	.....	.....	.....	28.50	28.33	28.42

Mirror extensometer readings did not give values for the plastic yield of the specimen, as differentiated from the elastic yield, since nearly all this plastic yield occurred during the preliminary loading and unloading period. For some runs, an extra long specimen was used, and a second, less sensitive extensometer was attached in tandem with the mirror extensometer so as to obtain a separate record of the total yield.

The results of typical tests belonging to this second series are summarized in Tables II, III, and IV, and in Fig. 4. A study of these tables shows in each case a relatively consistent decrease in modulus of elasticity, this decrease being evident at loads well below the yield point. The readings in fact indicate that this change in modulus of elasticity is continuous, beginning at the smallest stresses with which it was possible to work. In other words, at least for the particular materials here tested, the stress-strain line when carefully measured was a continuous curve, the slope changing by 2 to 4 per cent within the elastic range of the material as usually determined.

TABLE IV.—MODULUS OF ELASTICITY.

Hard-rolled spring-tempered phosphor-bronze strip $\frac{1}{8}$ by $\frac{1}{2}$ in.

Stress Range, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.		
	Initial Series	After Stressing at 75 600 lb. per sq. in.	After Stressing at 107 100 lb. per sq. in.
1 500 to 12 600	14 670 000	14 700 000	14 640 000
6 300 to 18 900	14 530 000	14 610 000	....
12 600 to 25 200	14 690 000	14 620 000	14 360 000
18 900 to 31 500	14 490 000	14 550 000	....
25 200 to 37 800	14 630 000	14 620 000	14 250 000
31 500 to 44 100	14 520 000	14 520 000	....
37 800 to 50 400	14 620 000	14 520 000	14 320 000
44 100 to 56 700	14 470 000	14 500 000	....
50 400 to 63 000	14 240 000	14 360 000	14 150 000
56 700 to 69 300	14 110 000	14 190 000	....
63 000 to 75 600	14 020 000	14 090 000	14 140 000
69 300 to 81 900	....	14 190 000	....
75 600 to 88 200	....	14 070 000	13 970 000
81 900 to 94 500	....	13 940 000	....
88 200 to 100 800	....	13 850 000	13 860 000
94 500 to 107 100	....	13 680 000	13 690 000

It is naturally desirable that any such conclusion as this be checked by other methods. For this reason, a third series of tests, using a very long gage length, carefully controlled temperature conditions, and dead weight loading, was initiated.

There was available in the college laboratory a standpipe, 5 ft. in diameter by somewhat over fifty feet high, with conical bottom and open top, which was used occasionally for hydraulic experiments. A hole was cut in the conical bottom, 4 in. from the circumference, and a 2-in. vertical steel pipe was placed in the standpipe above this hole, extending to slightly above the top of the tank. In this pipe were suspended two wires of the same material, a test wire and a comparison wire. At the upper end, both wires could be sighted by a micrometer-microscope through a hole in the 2-in. pipe, and any vertical movement of either wire could be measured. At the lower end the comparison wire was connected to a lever, to which a small constant load was attached, and the test wire was attached to a basket, which could be loaded with standard weights. Movement of a gage point on the comparison wire, located just below the point where it emerged from the standpipe, was measured by a micrometer-microscope, and movement of the gage point on the test wire was measured by a Gaertner cathetometer, with a 100-mm. lead screw. The overall

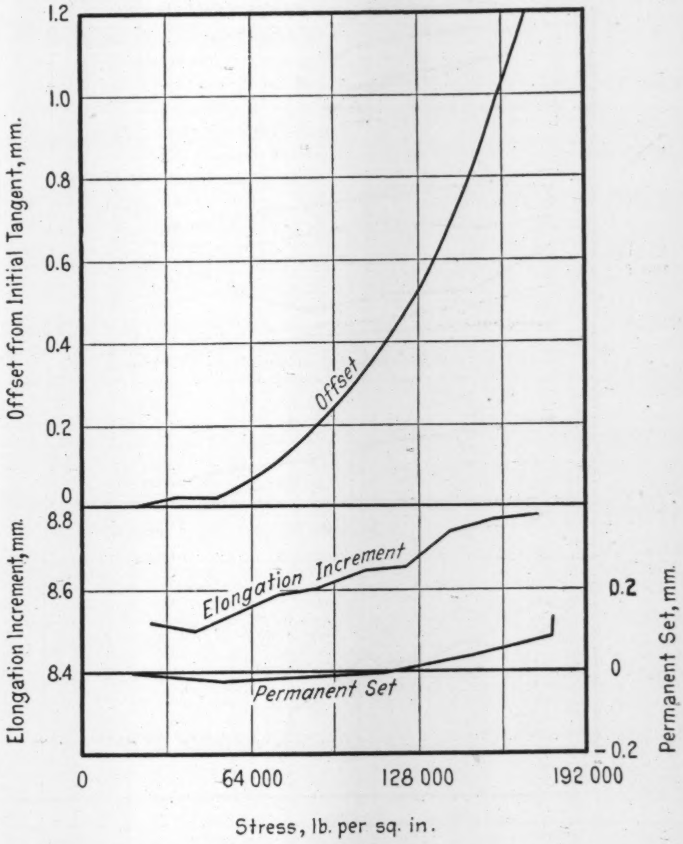

FIG. 3.—Elongation Resulting from Stress Increase of 16,000 lb. per sq. in.

gage length was approximately 15,750 mm., and each scale division on the cathetometer drum 0.005 mm.

The standpipe was filled with water to within a few inches of the top, so holding the temperature of the 2-in. pipe essentially constant during runs. Drafts of air up the pipe were prevented by lightly tucking a little cotton wool around the wires at the lower end of the pipe. The true elongation of the test wire under a given load was taken as equal to the change in the cathetometer reading, less the movement of the test wire at the top as given by the micrometer-

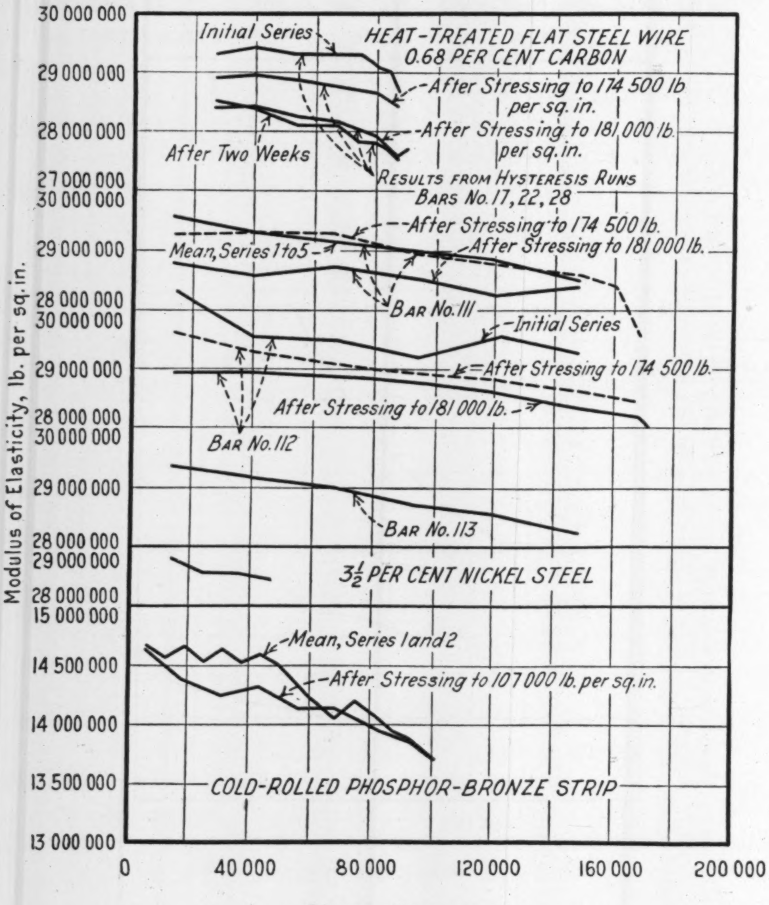

FIG. 4.—Showing Variation of Modulus of Elasticity with Unit Stress. Tests using Amsler machine.

microscope, corrected for any change in readings on the comparison wire which simultaneously occurred.

TABLE V.—TYPICAL STRESS-STRAIN DATA.

Tests on long wire specimens.

Stress, lb. per sq. in.	Strain, mm.					Modulus of Elasticity, lb. per sq. in.		
	Readings			Increment				
	Up	Down	Mean	Up	Down	Up	Down	Mean
0.67 PER CENT CARBON HEAT-TREATED STEEL WIRE, 0.0281 IN. IN DIAMETER. GAGE LENGTH 15,745 MM. DEAD WEIGHT LOADING. AVERAGE OF THREE RUNS, WIRE NO. 481. TEMPERATURE 17° C. (62.6° F.).								
19 340	0.050	0.064	0.058	.....	.....	....	....	....
35 460	8.551	8.578	8.565	8.501	8.512	29 860 000	29 830 000	29 850 000
51 580	17.069	17.122	17.096	8.518	8.544	810 000	720 000	760 000
67 700	25.629	25.670	25.650	8.560	8.548	660 000	700 000	680 000
83 820	34.204	34.252	34.228	8.575	8.582	610 000	580 000	600 000
99 940	42.835	42.870	42.852	8.631	8.618	420 000	460 000	440 000
116 060	51.491	51.532	51.512	8.656	8.662	330 000	310 000	320 000
132 180	60.203	60.248	60.225	8.712	8.716	140 000	130 000	140 000
148 300	68.964	......	68.964	8.761	8.716	28 980 000	29 130 000	060 000
17SRT ALUMINUM WIRE, 0.065 IN. IN DIAMETER. GAGE LENGTH 15,740 MM. DEAD WEIGHT LOADING. AVERAGE OF FIVE RUNS, WIRE NO. 483. TEMPERATURE 22.5° C. (72° F.).								
6 025	0.026	0.070	0.048	.....	.....	....	....	....
9 037	4.663	4.731	4.697	4.637	4.661	10 226 000	10 173 000	10 200 000
12 050	9.326	9.396	9.361	4.663	4.665	10 169 000	10 165 000	10 167 000
15 060	14.013	14.088	14.050	4.687	4.692	10 116 000	10 106 000	10 111 000
18 075	18.706	18.795	18.750	4.693	4.707	10 102 000	10 074 000	10 088 000
21 090	23.415	23.473	23.444	4.709	4.678	10 069 000	10 136 000	10 102 000
24 100	28.140	28.207	28.174	4.725	4.734	10 036 000	10 016 000	10 026 000
27 110	32.876	32.932	32.904	4.736	4.725	10 012 000	10 036 000	10 024 000
30 125	37.659	......	37.659	4.783	4.727	9 914 000	10 031 000	9 972 000
0.67 PER CENT CARBON HEAT-TREATED STEEL WIRE, 0.0465 IN. IN DIAMETER. GAGE LENGTH 15,751 MM. DEAD WEIGHT LOADING. AVERAGE OF FIVE RUNS, WIRE NO. 479. TEMPERATURE 21° C. (69.8° F.).								
17 670	......	[a]	......	.....	.....	....	....	....
35 330	......	[a]	......	9.280	9.301	29 990 000	29 920 000	29 960 000
53 000	......	[a]	......	9.326	9.303	29 840 000	29 920 000	29 880 000
70 670	......	[a]	......	9.352	9.357	29 760 000	29 740 000	29 750 000
88 340	......	[a]	......	9.396	9.358	29 620 000	29 740 000	29 680 000
106 000	......	[a]	......	9.416	9.436	29 560 000	29 500 000	29 530 000
123 670	......	[a]	......	9.505	9.425	29 280 000	29 530 000	29 400 000
141 340	......	[a]	......	9.498	9.471	29 300 000	29 390 000	29 340 000
159 000	......	[a]	......	9.570	9.526	29 080 000	29 220 000	29 150 000
176 680	......	[a]	......	9.604	9.562	28 980 000	29 110 000	29 050 000
194 350	......	[a]	......	9.638	9.579	28 880 000	29 060 000	28 970 000
212 000	......	[a]	......	9.706	9.592	28 680 000	29 020 000	28 850 000

[a] This group of runs was taken as a series of closed loops, taking readings 30 to 90 lb. actual load and return, then 90 to 150 lb., 150 to 210 lb., etc., in order to reduce the hysteresis and creep effects within each loop. As a result, it is not conveniently possible to give sets of mean readings.

RESULTS OF TESTS

Typical corrected elongations and moduli of elasticity as obtained by the method just described are given in Table V. Modified stress-strain curves are given in Fig. 2. In this figure the vertical scale represents the true stress in the wire but the horizontal scale represents the offset, in millimeters, from an initial tangent drawn to the stress-strain line. In this way the deviations from straight-line behavior were magnified so that they could be readily seen and so that the shape of the hysteresis loop could be observed.

Figure 3 shows these same results in a somewhat different fashion. It also shows the magnitude of the permanent set resulting from the application of various loads to the wire. This did not reach 0.05 mm., or one part in 300,000, until the stress reached 160,000 lb. per sq. in. It will be noticed that both the width of the hysteresis loop (as given in Fig. 2) and the amount of the permanent set, are small as compared to the variations in the elongation increments and to the offsets from the initial tangent, so that these variations apparently represent the true elastic behavior of the materials rather than deviations from it.

TABLE VI.—MODULUS OF ELASTICITY.

Specimen	Material	Temperature		Modulus of Elasticity, lb. per sq. in.[a]
		deg. Cent.	deg. Fahr.	
No. 481	0.67 per cent carbon heat-treated steel wire, 0.0281 in. in diameter	16.8	62.6	30 040 000 − 6.6S[b]
No. 479	0.67 per cent carbon heat-treated steel wire, 0.0465 in. in diameter	20.7	69.8	30 160 000 − 6.5S[b]
No. 111	0.68 per cent carbon heat-treated steel wire, $\frac{1}{8}$ by $\frac{1}{2}$ in. in diameter	24.4	76	29 700 000 − 7.7S
No. 112	0.68 per cent carbon heat-treated steel wire, $\frac{1}{8}$ by $\frac{1}{2}$ in. in diameter	24.4	76	30 100 000 − 6.8S
No. 113	0.68 per cent carbon heat-treated steel wire, $\frac{1}{8}$ by $\frac{1}{2}$ in. in diameter	24.4	76	29 500 000 − 8.3S
No. 530 No. 538	$3\frac{1}{2}$ per cent nickel steel, $\frac{1}{2}$ in. in diameter	25.6	78	29 140 000 − 4.3S
No. 476	$3\frac{1}{2}$ per cent nickel steel, $\frac{1}{2}$ in. in diameter	22.8	73	28 930 000 − 10.9S
No. 306	Spring tempered phosphor-bronze, $\frac{1}{8}$ by $\frac{1}{2}$ in. in diameter	22.2	72	14 680 000 − 10.8S
No. 483	17SRT aluminum alloy wire, 0.065 in. in diameter	22.5	72.5	10 280 000 − 10.9S[b]

[a] S = unit stress in tension, pounds per square inch.

[b] These figures were obtained using dead weight loading and long gage length, and are somewhat more reliable than the other figures.

As obtained from the data so far available, the values of modulus of elasticity given in Table VI are tentatively suggested. It should be emphasized that these values represent only the particular materials tested. A large amount of time and attention has been required for each series of tests, and therefore only a limited variety of samples have been tried. The investigation has not yet gone far enough to justify conclusions as to whether the rate of change of modulus of elasticity is a definite characteristic of the material or whether it varies with different types of heat treatment or of mechanical work. Further experiments are in progress to cover some of these points.

. . . .

CONCLUSIONS

In typical elastic materials such as phosphor-bronze, heat-treated carbon spring steel, nickel steel, and high-strength aluminum-alloy wire, the true elastic stress-strain line appears to be continuously curved, there being a difference of from 2 to 4 per cent between the slope at zero load and the slope at the elastic limit. The more carefully the measurements are made, the more definitely is this curvature shown. The deviations from straight line behavior are not great enough to affect the accuracy of stress calculations based on the usual elastic theory, particularly for the low stresses used in most design work. They are great enough, however, to cause considerable discrepancies in high-strength material between the true elastic limit and the apparent proportional limit as usually determined.

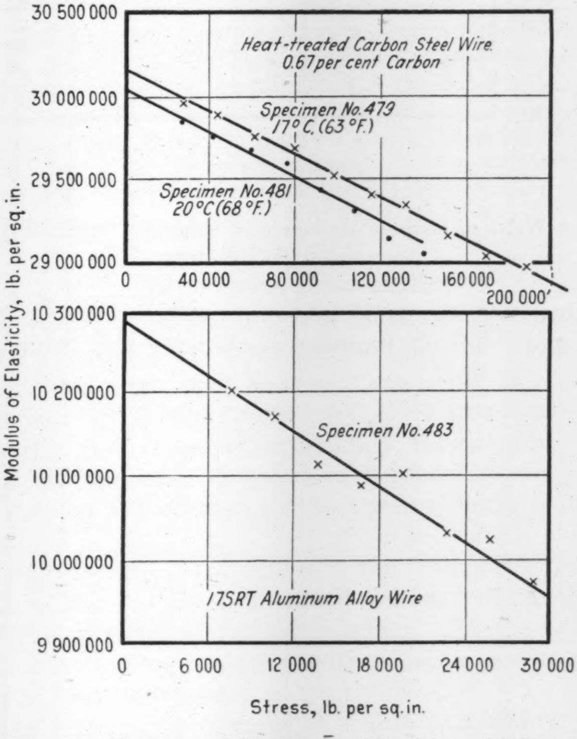

FIG. 5.—Showing Variation of Modulus of Elasticity with Unit Stress. Tests made on long wires with dead weight loading.

The evidence in favor of this curved stress-strain line is considerably increased by the fact that for some time past the theories regarding the nature of atomic attraction and repulsion have called for just such curvature. This curvature should be such that the modulus of elasticity would decrease with increasing stress in tension, and increase with increasing stress in compression. Work is planned on the much more difficult problem of checking this behavior in compression.

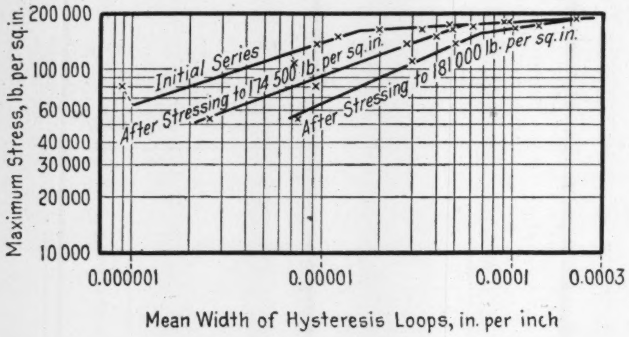

FIG. 6.—Mean Width of Loop for Hysteresis in Tension. Bars Nos. 17, 22 and 28, heat-treated flat steel wire.

HARDNESS BY MUTUAL INDENTATION

By Irving H. Cowdrey[1]

Synopsis

Mutual indentation has long been recognized as a practicable method for determining hardness. Several investigators have made use of it with crossed prisms and cylinders using various functions of the indentation and load as hardness indicators. The author has made use of both crossed and parallel cylinders and has shown that in each case a simple linear function suffices to transform the resultant data to Brinell hardness. This transformation constant appears to be independent of material, size and proportions of the test cylinders, and over a reasonable range independent of the pressure used.

Historical Precedent

The fundamental principle at the foundation of the method to be presented is in no sense new; hardly is it even modern. More than two hundred years ago, Reaumur[2] made use of it by pressing together 90-deg. prisms edge to edge with their axes crossed as shown in Fig. 1. His work, however, apparently did not advance beyond the attempt to determine the relative hardness of the two prisms which was held to be indicated by the relative depth of the mutual impressions.

Later Foeppl[3] varied and extended the method by using crossed cylinders as in Fig. 3. He also defined the hardness of the material as pressure per unit area of flattened surface. This means of definition later became also the basis of the Brinell scale of hardness though the method of indentation became greatly modified. In 1920 Haigh[4] published the results of a research in which he modified Reaumur's method by using square prisms as shown in Fig. 2. He suggests the use of this shape of test specimen since it is readily available when Charpy or Izod tests have been conducted. In the development of his paper he points out the fact that when the prisms are alike in shape and hardness the indentations produced are of identical form and within reasonable ranges of load there is a constant proportionality between this load and the square of any linear dimension. He then defines his hardness scale by the equation:

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[1] Associate Professor of Testing Materials, Massachusetts Institute of Technology, Cambridge, Mass.

[2] Reaumur, "L'Art de Convertir" (1722).

[3] Foeppl, Ann. Phy. Chem., Vol. 1, pp. 103–108.

[4] Haigh, "Prism Hardness," *Proceedings*, Inst. Mechanical Eng., October, 1920, pp. 891–913.

$$\text{Prism Hardness} = \frac{W}{X^2}$$

where W = load applied in tons or kilograms, and
X = length of the indentation along the edge of the prism in inches or millimeters.

Hence it is obvious that this method would add a new scale of hardness to a family now altogether too large. After expressing Brinell hardness in tons per square inch, (instead of the usual kilograms per square millimeter) he found the ratio of Brinell hardness to prism hardness equal to 1.5 to 2.1 for the materials investigated.

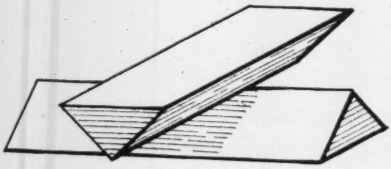

FIG. 1.—Reaumur Method.

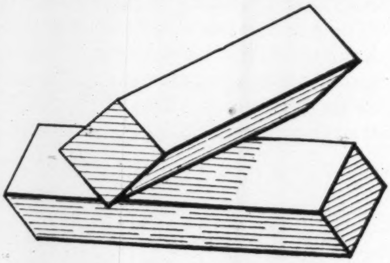

FIG. 2.—Haigh Method.

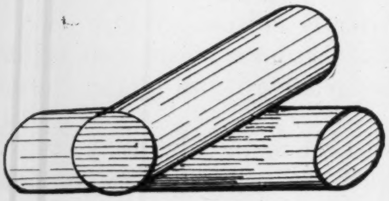

FIG. 3.—Foeppl Method.

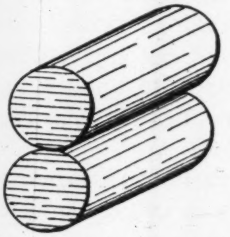

FIG. 4.—Cowdrey Method.

CROSSED CYLINDERS (FOEPPL'S METHOD)

During the early part of 1923, a short study of Foeppl's[1] method was conducted under the direction of the author. Since the standard Brinell ball is 10 mm. in diameter it was felt that cylinders of that diameter would be a logical size and such were used. When cylinders crossed as in Fig. 3, are subjected to load, the mutual indentations are practically circular in vertical projection: actually they are saddle-shaped surfaces. While Foeppl defined hardness as "pressure per unit area of the indentation," in this series of tests no attempt was made to determine the true area of the impression. The diameter of the dent can be most easily and accurately determined along the element of initial contact. These diameters are used as the abscissas in plotting Fig. 5.

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[1] Thesis: H. D. Follansbee, Jr., Department of Mechanical Engineering, Massachusetts Institute of Technology.

Standard Brinell tests were also made on the same specimens and the diameters of these indentations used for the ordinates in the same figure. It is readily apparent that a simple linear relation exists between the two types of indentation. Within the range studied this relation may be expressed as:

$$B = 0.3 + 0.85\,C$$

where B is the diameter of the Brinell indentation, and C the diameter of the mutual indentation using 10-mm. crossed cylinders as in Fig. 3. Hence it is perfectly obvious that this method may be used to give actual Brinell values. The observed diameter of the mutual impression, C, may be transformed to equivalent Brinell impression, B, and this derived value then used with the Brinell chart for determining the actual Brinell hardness number.

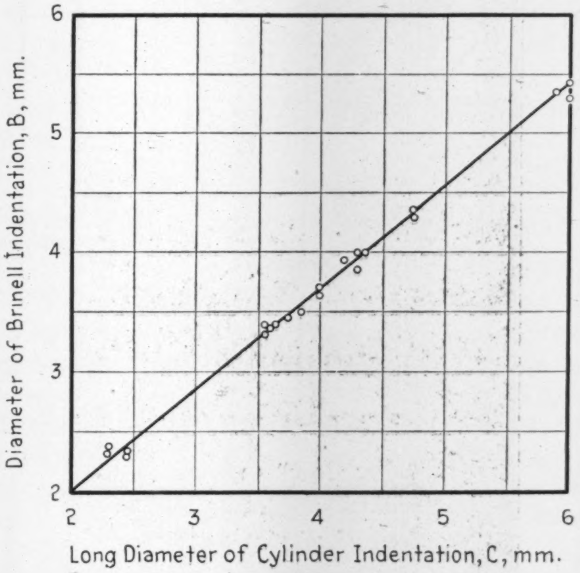

FIG. 5.—Showing Relation of Brinell Indentations and the Cylinder Indentations.

MUTUAL INDENTATION USING PARALLEL CYLINDERS

For many years the Brinell hardness scale has been looked upon as standard in this country. Every new method of hardness testing has found it advisable if not necessary to express itself in terms of the established Brinell scale. The research under discussion was not intended to introduce any new scale of hardness measurement; it was merely desired to develop another method whereby Brinell hardness may be obtained under conditions which would make the present method difficult or impossible.

In order that this might be accomplished with minimum difficulty, it seemed desirable that the mutual indentations should approximate plane surfaces with simple geometric outline. If such conditions could be produced, the area of these indentations would be determinable with little difficulty and fair accuracy. It seemed that such results might best be obtained by means of identical cylinders loaded in elemental contact with parallel axes as in Fig. 4.

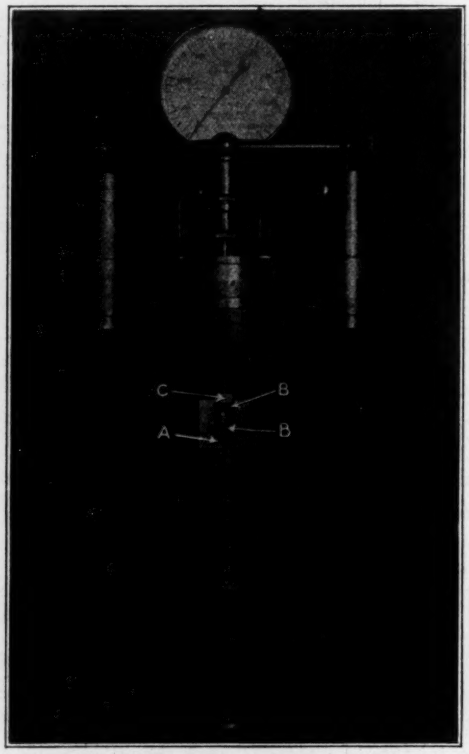

FIG. 6.—Loading Apparatus Assembled in a Standard Brinell Hardness Testing Machine.

With this premise an investigation was conducted[1] under the direction of the author. The method of holding and loading the test cylinders is clearly shown in Fig. 6.

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[1] Thesis: O. V. Aros and R. P. Delano, Jr., Department of Mechanical Engineering, Massachusetts Institute of Technology, 1929.

Variables Studied:

In this investigation it was desired to study the following variables:

1. Size of cylinder;
2. Ratio of length to diameter of cylinder;
3. Total pressures between 500 and 3000 kg.

From the data obtained it was expected that some combination might be developed such that:

$$\frac{\text{Applied Load (in kilograms)}}{\begin{array}{c}\text{Area of Mutual Indentation}\\ \text{(in square millimeters)}\end{array}} = K \times \text{Brinell Hardness Number}$$

In case the relation did not prove linear as indicated above, it was hoped that it might develop into some simple function.

The metals chosen for this study were the following:

MATERIAL	BRINELL HARDNESS NUMBER
Duralumin	54
Low Carbon Steel	90
Brass	120
Chromium-Vanadium Steel	150
Silicon-Chromium Steel	180
High-Carbon Steel Drawn at 600° F	440
High-Carbon Steel Quenched from 1550° F	650

It was felt that this group of materials gave a reasonable range of hardness and that the values of the Brinell hardness number were sufficiently well spaced so that some mathematical law might be deduced if the results proved consistent. Moreoever, the insertion of two non-ferrous materials might indicate whether or not the relation to be deduced might be reasonably comprehensive or be confied to ferrous metals only. The alloy steels also might be expected to act as indicators for the various ferrous groups.

Apparatus and Method of Test:

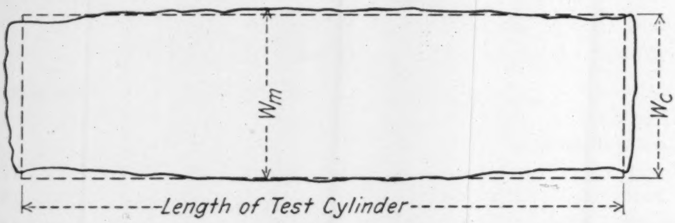
The investigation was to be conducted by means of a Brinell machine of Swedish manufacture. Since relative results were to be the principal objective and both the Brinell numbers and the mutual indentation numbers were determined by the same machine, the absolute precision of the machine is not a factor in this analysis.

It was essential that the cylinders be held in accurate alignment. The device used shown in Fig. 6 consists of a rigid block, *A*, that rests directly on the Brinell screw. The blocks *B B* are the halves of a single alloy steel block which was drilled and reamed to the size desired, then split with a narrow milling saw and hardened. After hardening they were ground to fit the slot in the guide block *A*.

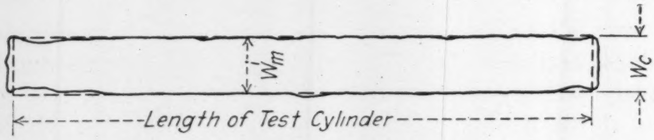
Three sets of blocks were made to take the three cylinder diameters to be used, namely, 15, 10 and 5 mm. A loading block, *C*, was threaded to fit the end of the Brinell ram.

With the apparatus assembled in this manner, loads could be applied as in a regular Brinell test in multiples of 500 kg. up to the standard 3000 kg. The mutual indentation of the two cylinders resulted in the production of flattened areas which under reflected light appeared as true planes. The outline of these areas was sensibly rectangular to the naked eye.

It was purposed to read the width of this flattened area with the usual Brinell microscope and use as area this width times the length of the test cylinder. Under the Brinell microscope it became evident that the area of the indentation was not a true rectangle. This is not surprising since some flow of metal lengthwise of the cylinder must be expected. In order to study the actual conditions several of the flattened areas were studied by low-power micro-projection (about 13 diameters enlargement in the original observations). The enlarged areas were projected against tracing paper and the outline penciled as carefully as possible. At the same time the apparent original length of the test cylinder was recorded for use in the subsequent calculations. Two such tracings are reproduced in Figs. 7 (*a*) and (*b*). The original tracings were about 5 in. long.



(*a*) Chromium-vanadium steel cylinder, diameter, 10 mm., length, 10 mm.



(*b*) Silicon-chromium steel cylinder, diameter, 5 mm., length, 10 mm.

FIG. 7.—Tracings of Enlarged Areas.

Solid outline traced from micro-projection of the flattened area. Length of cylinder is shown at same magnification.

Dotted outline shows rectangle of same area as that within the traced outline.

The widths, marked W_m are the values which would be recorded if the width of the flattened area were measured with the common Brinell microscope.

The actual enlarged area was measured by a planimeter. The rectangle shown dotted has been constructed using the cylinder length as a base and making W_c of such a magnitude that:

Area of rectangle = traced area of the flat.

It should be noted that there is very little difference between W_m and W_c.

The areas shown in Figs. 7 (*a*) and (*b*) showed the following properties:

	FIG. 7 (*a*)	FIG. 7 (*b*)
W_m (original tracing), in. =	1.52	0.48
W_c (original tracing), in. =	1.503	0.478
Difference, per cent =	1.1	0.2
W_m (natural size), mm	2.97	0.97
W_m (measured by Brinell microscope), mm	3.00	0.90
Difference, per cent	1.0	7.8

It seems reasonable to presume that the value W_m measured from the enlarged projection and reduced to millimeters should be more nearly correct than that obtained by reading directly with the Brinell microscope. From the data above and this last consideration it would appear that the error in assuming that the area of indentation $= W_m \times L$ is less than the error to be expected in measuring W_m, the original length of the test cylinder being L.

Consequently in the data to be recorded later the maximum width of the flattening has been noted with the Brinell microscope and multiplied by the length of the test cylinder to determine the area of the mutual indentation.

Hardness Scale Defined:

Following the analogy of the Brinell definition for hardness, the author proposes to define hardness when determined by this method as the quotient of load divided by the area of the mutual indentation. This might be expressed in any convenient units of force and area. Metric units will be used in this discussion. Hence:

$$\text{Cylinder Hardness Number} = \frac{P}{A} = \frac{P}{WL}$$

where P = load in kilograms,
A = area of the mutual indentation,
W = width of indentation measured in millimeters, as previously described, and
L = original length of test cylinder in millimeters.

Test Cylinders:

In the original scheme, it was intended to use cylinders of three diameters (15, 10, and 5 mm.). For each diameter it was intended to use three lengths: $L = 0.5\ D$, $L = D$ and $L = 1.5\ D$. Such proportions would have given the smallest test cylinder the dimensions $D = 5$ mm., $L = 2.5$ mm., and for the largest cylinder $D = 15$ mm., $L = 22.5$ mm.

Such proportions would have made the smallest cylinder altogether too small to handle. Moreoever, with the softer materials the cylinders with $D = 10$ mm. and $L = 5$ mm. gave trouble by indenting irregularly and slipping endwise. Trial tests also showed that cylinders having dimensions $D = 15$ mm. and $L = 22.5$ mm. in the case of the harder steels were of a proportion that the full load of the Brinell machine produced flattening too small to give satisfactory readings.

As a consequence of such preliminary study, it was decided to use the following proportions for the test cylinders.

DIAMETER, MM.	LENGTH, MM.
5	10
10	10 15
15	10 15

All five sizes were tested for each of the materials studied except the high-carbon steel as will appear in a later tabulation.

Loads Used:

Just as with the standard Brinell method, certain pressures seem best fitted to various metals or conditions, so in this investigation certain metals and certain sizes of cylinders gave best results under particular loads. In most cases at least two different loadings were found practicable. When studying the brass it was found possible to obtain workable indentations with loads running over the full range from 500 kg. to 3000 kg. Also in most instances some particular load proved satisfactory for all the cylinder sizes used.

Results:

The results of the tests are expressed in Table I.

An examination of the above data shows the ratio of Brinell hardness number to cylinder hardness number to be sensibly a constant regardless of the many variables which have been introduced into the test. Hence it is obvious that a plot showing the relation

TABLE I.—RESULTS OF HARDNESS TESTS OF VARIOUS METALS.

Load, kg.	Cylinder Dimensions		Indentation Dimensions		Cylinder Hardness Number	Ratio, Brinell Hardness to Cylinder Hardness
	Diameter, mm.	Length, mm.	Width, mm.	Area, sq. mm.		
DURALUMIN—BRINELL HARDNESS, 54						
500	5	10	1.45	14.5	34.5	1.56
	10	10	1.45	14.5	34.5	1.56
	10	15	0.95	14.3	35.0	1.54
	15	10	1.40	14.0	35.6	1.51
	15	15	0.95	14.3	35.0	1.54
1 000	10	10	2.80	28.0	35.6	1.51
	10	15	1.90	28.5	35.0	1.54
	15	10	2.75	27.5	36.4	1.48
	15	15	1.90	28.5	35.0	1.54
Average					35.2	1.53
Average deviation, per cent						1.4
Maximum deviation, per cent						3.3
BRASS—BRINELL HARDNESS, 120						
500	5	10	0.65	6.5	77.0	1.56
1 000	5	10	1.30	13.0	77.0	1.56
	10	10	1.25	12.5	80.0	1.50
	10	15	0.85	12.8	78.5	1.53
	15	10	1.30	13.0	77.0	1.56
	15	15	0.85	12.8	78.5	1.53
2 000	10	15	1.70	25.5	78.5	1.53
	15	10	2.60	26.0	77.0	1.56
	15	15	1.65	24.8	80.5	1.49
3 000	10	10	3.80	38.0	79.0	1.52
Average					78.5	1.53
Average deviation, per cent						1.3
Maximum deviation, per cent						2.6
SILICON-CHROMIUM STEEL—BRINELL HARDNESS, 180						
1 000	5	10	0.90	9.0	111	1.62
	10	10	0.90	9.0	111	1.62
	10	15	0.60	9.0	111	1.62
	15	10	0.90	9.0	111	1.62
	15	15	0.60	9.0	111	1.62
3 000	10	10	2.60	26.0	116	1.55
	10	15	1.70	25.5	118	1.53
	15	10	2.50	25.0	120	1.50
	15	15	1.70	25.5	118	1.53
Average					114	1.58
Average deviation, per cent					......	2.9
Maximum deviation, per cent					......	5.0
Using 3000-kg. load only:						
Average					118	1.53
Average deviation, per cent					......	0.8
Maximum deviation, per cent					......	2.0
LOW-CARBON STEEL—BRINELL HARDNESS, 90						
1 000	5	10	1.70	17.0	58.9	1.53
	10	10	1.80	18.0	55.5	1.62
	10	15	1.20	18.0	55.5	1.62
	15	10	1.80	18.0	55.5	1.62
	15	15	1.20	18.0	55.5	1.62
2 000	10	10	3.40	34.0	58.9	1.53
	15	10	3.40	34.0	58.9	1.53
	15	15	2.30	34.5	58.0	1.55
3 000	10	15	3.40	51.0	58.9	1.53
Average					57.3	1.57
Average deviation, per cent						2.8
Maximum deviation, per cent						3.2
CHROMIUM-VANADIUM STEEL—BRINELL HARDNESS, 150						
1 000	5	10	1.05	10.5	95.0	1.58
	10	10	1.15	11.5	87.0	1.72
	10	15	0.80	12.0	83.3	1.80
	15	10	1.15	11.5	87.0	1.72
	15	15	0.70	10.5	95.0	1.58
3 000	10	10	3.00	30.0	100.0	1.50
	10	15	1.90	28.5	105.0	1.43
	15	10	3.10	31.0	97.0	1.54
	15	15	2.00	30.0	100.0	1.50
Average					94.4	1.60
Average deviation, per cent					......	6.3
Maximum deviation, per cent					......	12.5
Using 3000-kg. load only:						
Average					100.5	1.49
Average Deviation, per cent					......	2.2
Maximum deviation, per cent					......	4.0
HIGH-CARBON STEEL—BRINELL HARDNESS, 440						
3 000	5	10	1.00	10.0	300	1.47
	10	10	1.00	10.0	300	1.47
	15	15	0.70	10.5	286	1.54
Average	......	......	......	......	295	1.49
Same hardened (Brinell Hardness Number)						650
3 000	5	10	0.70	7.0	429	1.52
	10	10	0.70	7.0	429	1.52
Average	......	......	......	......	429	1.52

between the two scales will be a straight line. In fact, any plot that could be reasonably reproduced in this paper would be of such a scale that the deviation of individual points from a straight line could not be satisfactorily shown. For this reason such a graph has been omitted. It is well understood that light loads with the Brinell machine do not yield satisfactory indentations. The discrepancies appearing with 1000-kg. loads for the harder steels are then not surprising. It is felt that they may properly be omitted from the following discussion. Using the remaining 41 tests the value of the quotient of Brinell hardness number divided by cylinder hardness number is 1.53, the maximum deviation from this value is 6.5 per cent; the average deviation, 1.9 per cent. If the results of the 1000-kg. pressure were omitted for all the steels the above relations become 1.52, maximum deviation from the mean, 5.9 per cent and average deviation from the mean, 1.4 per cent. The relation between the scales if proper loads be used to meet the conditions at hand may therefore be expressed:

Brinell hardness number = 1.52 Cylinder hardness number.

CONCLUSIONS

From the foregoing data and analysis it may be concluded:

1. Mutual indentation of equal cylinders made from the same material, pressed together under proper loads while their axes are maintained parallel, affords a means of determining Brinell hardness.
2. Over a wide range of material and hardness there is a constant relation between the Brinell hardness and the quotient obtained by dividing the load applied by the area of the mutual indentation produced.
3. This relation appears to be independent of size and proportion of cylinders between fairly wide limits.
4. This relation appears independent of the load when the Brinell hardness is less than 150. With higher values of Brinell hardness, it appears necessary to use pressures not less than 3000 kg.

EXTENSIONS AND APPLICATIONS OF THIS METHOD

While it was the original intent to show merely that the method previously described would yield results readily convertible into Brinell values, it seems that it may have a wider scope. The constant introduction of harder and harder alloys has made the measurement of their hardness a problem of progressively increasing difficulty. As the hardness of these materials approaches that of the Brinell ball, its determination becomes more and more unreliable. Mutual indentation entirely eliminates this difficulty. No matter how hard the material, the method under consideration may be used, provided cylinder sizes and proportions can be found such that a flattened area will be produced of measurable width without shattering the test specimens. It is believed that the smallest usable diameter gives the best results because the angle between the flattened area and the cylindrical surface is sharpest under those conditions. Thus the width is read with the best precision. It is also obvious that the heavier loads are to be preferred. The pressures must not, however, be carried to such magnitudes that the metal of the cylinder begins to flow as a whole. When the metallic flow ceases to be local and becomes general, properties and characteristics are brought into evidence which are not at all definable as hardness.

By means of mutual indentation, tests may be made at temperatures which are not feasible using the Brinell method directly. Certain experimenters have utilized the Brinell ball for testing hardness at forging heats. Such procedure is attended with some difficulty. Great speed of manipulation is necessary, some "scaling" difficulties may be encountered, and there is every chance that, even under quickly applied loading, softening of the ball may be experienced. All of these objections may be eliminated when test specimen and indentor are identical and mutually interchangeable.

The hardness of stellite, high-speed steels and such material might well be studied by this method, for temperatures known or believed to exist during machining operations. The immersion of the cylinders, pressure, and guide blocks in an oil or lead bath during test would present very little difficulty. An electric heating coil and a pyrometer would serve for control and record of temperature.

At times it becomes desirable to study the hardness of small rods or wire. Since these are drawn accurately to circular cross-section it only becomes necessary to cut short pieces of equal length and treat them as already described. With special devices for holding, it is thought possible to determine the hardness of wires only a few millimeters in diameter. In some cases where very small wires are used the crossed cylinder method may prove more feasible. Possibly special scales may need to be devised by each user. Even so it seems to the author that such special scales might furnish an easy and rapid check on the quality of the product, the degree of cold working, the toughness or brittleness, and possibly other factors which often give trouble in wire products.

As appears in the previous description, the tests herein outlined made use of accurately fitted loading blocks which supported the test cylinders over nearly half their surfaces. It is possible that such refinement may not be necessary. The author expects to extend the research to study the possibility of using V-blocks in place of the semicylindrical blocks. If such modification is found possible, then certain of the manipulative objections disappear. A very few pairs of blocks will suffice to care for a wide variety of cylinder sizes.

For surface-hardened material it is not expected that this method will give any satisfactory information. It would appear that bearing metals would lend themselves admirably to this method of study.

DISCUSSION

MR. S. N. PETRENKO[1] (*presented in written form*).—The paper by Mr. Cowdrey is a valuable contribution to our general knowledge of the indentation hardness phenomenon.

The fact that the ratio of Brinell hardness number to cylinder hardness number is not equal to 1 is not surprising when the differences in the test conditions are considered. The apparent constancy of this ratio for all or nearly all loading conditions and materials which were used is a further proof that there is a more or less definite relation between the Brinell number and other mechanical properties of the materials.

As a practical method of determining indentation hardness, this two-cylinder test, however, does not appear to be very well adapted for the purpose. The chief advantage of the method which is based on mutual indentation of two geometrically identical bodies made from the same material is that the indentation numbers of extremely hard metals can be obtained with no greater difficulty than those of moderately hard metals. This advantage, however, is not of great practical importance because hardness testing machines, such as Rockwell and Vickers, using diamond indenting tools, have come into general use.

The Rockwell machine is well adapted for many commercial uses and is rapidly replacing some other hardness testing machines.

The Vickers machine is based on the Brinell principle and gives values which are much more closely related to Brinell numbers than are cylinder hardness numbers. Accurately shaped diamond indenting tools are now produced commercially. With these tools it is quite possible to obtain indentations in the hardest metals which can be accurately and readily measured.

Small loads and small indenting tools which give small indentations are evidently being more and more preferred in the testing practice to large loads and to large indenting tools. Whenever a necessity for having a large indentation arises, as in the case of some heterogeneous metals, such as cast iron, the metal is comparatively soft and the ordinary Brinell method can be successfully used.

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[1] Associate Mechanical Engineer, U. S. Bureau of Standards, Washington, D. C.

THE RATE OF HYDRATION OF CEMENT CLINKER[1]

PART II—PORTLAND CEMENT AT NINE AND TWELVE MONTHS

PART III—THREE MINERALS FOUND IN PORTLAND CEMENT

By F. O. Anderegg[2] and D. S. Hubbell[3]

Synopsis

Part II.—Standard portland cement particles, whose earlier reaction rate had been previously reported and whose original dimensions were 15 to 25 microns, were found to be approaching apparently complete hydration in nine months, while at twelve months hydration was practically finished. A white portland cement and an early-strength portland cement seemed to reach a similar degree of hydration in a shorter time.

Part III.—The hydration rate of tricalcium aluminate was found to be quite high, particles of a dimension of about 25 microns being about three-quarters hydrated in 3 hours. Tricalcium-silicate particles of the same size required about 7 days for a similar degree of hydration, while with dicalcium silicate this amount of hydration was reached only after 5.5 months. The early rates for the portland cements studied appeared to be intermediate between those of the two silicates. In general, mixtures of minerals reacted more rapidly than single minerals. This was true especially for the mixture roughly approximating the portland cement in composition.

PART II—PORTLAND CEMENT AT NINE AND TWELVE MONTHS

The methods described in the authors' paper before the Society last year[1] have been followed in obtaining and calculating the results reported here. (See Table I and Fig. 1.) During the investigation of the hydration rates of the pure minerals described in Part III, it was found advisable to grind the partially hydrated materials under oil. This raised the question as to whether partially hydrated commercial portland cements, on grinding in the air, might undergo further hydration. Direct comparisons between the two methods, however, showed that the two methods gave results checking within 1 per cent.

At 9 months the effect of calcium sulfate or chloride on the rate of hydration was negligible.

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[1] The first paper by the authors on this subject (Part I) was presented at the annual meeting of the Society in 1929; see *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 554 (1929).

[2] Senior Industrial Fellow, Mellon Institute of Industrial Research, Pittsburgh, Pa.

[3] Industrial Fellow, Mellon Institute of Industrial Research, Pittsburgh, Pa.

At 12 months the unhydrated residue was quite small.

The apparent depth of hydration of the standard portland cement (portland cement A) at 9 months was about 7.2 microns as compared with 3.54 at one month and 5.12 at 3 months.

TABLE I.—HYDRATION OF PORTLAND CEMENT AT LONGER PERIODS.

Mean Dimension, microns	Conditions	3½ months		5 months		9 months		12 months	
		Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns
	PORTLAND CEMENT A								
20.69...	Calcium sulfate added....	......	......	......	......	......	....	97.68	Complete
25.53...	Calcium sulfate added....	......	......	......	......	......	....	98.53	Complete
15.53...	No Calcium Sulfate added.............	......	......	......	......	95.78	5.07	97.33	Complete
20.69...		......	......	......	......	95.67	6.71	97.68	Complete
22.05...		......	......	......	......	94.00	6.71	97.79	Complete
23.57...		......	......	......	......	96.32	7.86	97.74	Complete
23.57...		......	......	......	......	......	....	98.09	Complete
25.53...		......	......	......	......	96.02	8.41	98.00	Complete
25.53...		......	......	......	......	94.17	7.81	98.53	Complete
27.45...		......	......	......	......	......	....	98.54	Complete
23.57...	$CaCl_2$ 0.7 per cent of cement and sulfate.......	......	......	......	......	96.32	7.86	98.09	Complete
20.69...	1.4 Normal Consistency..	......	......	......	......	......	....	97.84	Complete
							Average 7.20		
	PORTLAND CEMENT B								
26.73...	....	88.25	6.82	......	......	94.58	8.30	......	....
	PORTLAND CEMENT C								
27.13...	....	......	......	95.85	8.87	......	....	......	....
	WHITE PORTLAND CEMENT								
27.98...	....	......	......	91.77	7.90	......	....	......	....

The white portland cement was apparently more hydrated at 5 months than the standard gray cement (portland cement B) at 9 months.

At 5 months the high-early-strength portland cement (portland cement C) was more completely hydrated than any of the others.

PART III—THREE MINERALS FOUND IN PORTLAND CEMENT

Through the courtesy of R. H. Bogue, samples of tricalcium aluminate, tricalcium silicate, dicalcium silicate and calcium ferro-aluminate prepared by the Portland Cement Association Fellowship at the U. S. Bureau of Standards have been studied using the methods of experimenting and calculating previously described. A slight modification was introduced by grinding the partially hydrated mineral under oil because the speeds of reaction were such that progressive hydration occurred during grinding of these minerals in air.

The impurities in the minerals were determined by observing the optical properties of about one thousand particles of each fraction separated for the determination. Since there were four or five fractions of every mineral, the number of particles of each studied was in the neighborhood of four thousand. In tricalcium aluminate inert material to the extent of 1.7 per cent, mostly calcite, was found; in dicalcium silicate the inert substances aggregated 2.15 per cent, about one-half being calcite; while in tricalcium silicate the inert compounds were negligible, but the dicalcium silicate was found to be 8.85 per cent. A suitable correction was made for these impurities.

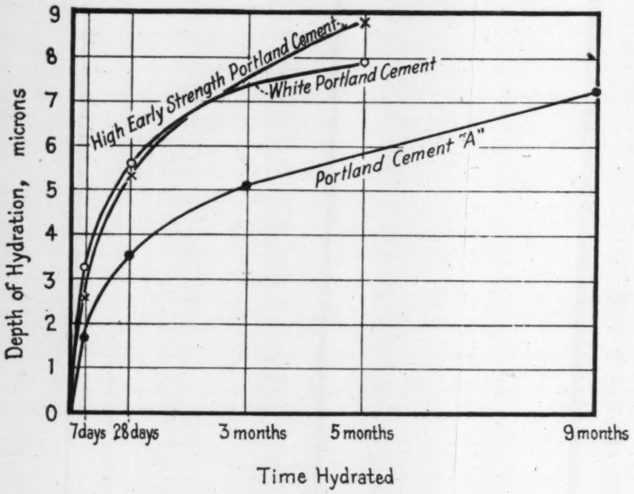

FIG. 1.—Depth of Hydration of Portland Cement Clinker at Given Time Intervais.

The specific gravities needed in the calculations were determined on the unhydrated, separated minerals and on those ground repeatedly with water. After the latter operation the portion remaining unhydrated was determined in the usual way by a special count. It was very small for the trisilicate and trialuminate, but rather large for the disilicate. The gravities observed before hydration were 3.026, 3.020 and 3.233 and after hydration and correction for unhydrated mineral, 2.15, 2.49 and 3.00, respectively. Thorvaldson, Grace and Vigfusson[1] report a density of 2.522 for $3\ CaO \cdot Al_2O_3 \cdot 6H_2O$.

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[1] T. Thorvaldson, N. S. Grace and V. A. Vigfusson, "The Hydration of the Aluminates of Calcium. II. The Hydration Products of Tricalcium Aluminate," *Canadian Journal of Research*, Vol. 1, p. 203 (1929).

The dicalcium silicate, both before and after hydration, appeared to be heaviest. The specific gravity of the partially hydrated dicalcium silicate appearing to be somewhat high, the determination was repeated giving results similar to those obtained during the first trial.

Calcium sulfate (1.6 per cent by weight as $CaSO_4\ 2H_2O$) was added in part of the experiments. A few mixtures of minerals were observed including one roughly approximating commercial portland cement in composition. Calcium ferro-aluminate was added in small amounts to each of the three minerals to see what effect the presence of this iron compound might have on the reaction rate of the others. Iron oxide, being positive in character, might join with the negative silica to form a more compact gel which could be expected to slow up the passage of the reacting water towards the unhydrated cores. However, no evidence in support of this supposition was obtained, probably because of the great reactivity of this compound itself for water.

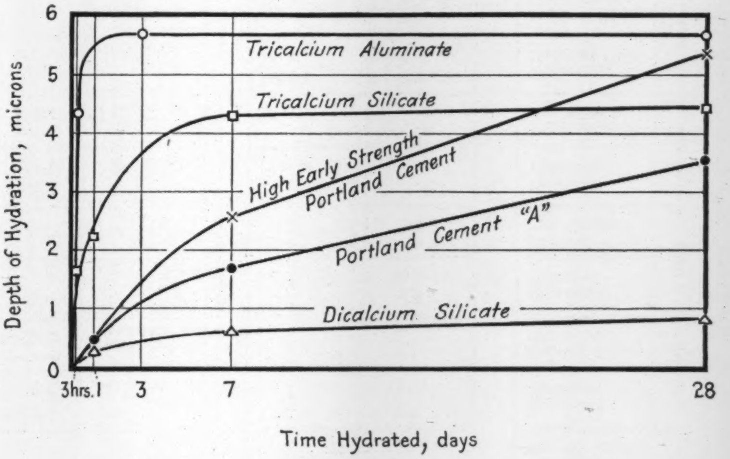

FIG. 2.—Depth of Hydration, at Given Time Intervals, of Several Minerals Found in Portland Cement.

The experiments were carried out at room temperature (70 ± 5° F.) and all specimens were stored in water until the reaction was stopped by sudden heating of the finely divided specimens. The data are presented in Table II and Fig. 2. Tricalcium aluminate was hydrated most rapidly of the three binary minerals. Tricalcium silicate was not far behind while dicalcium silicate had a comparatively slow reaction rate. The rates for the commercial portland cements were

TABLE II.—HYDRATION OF MINERALS FOUND IN PORTLAND CEMENT.

Mean Dimension, microns		1 minute		15 minutes		3 hours		24 hours		3 days		7 days		28 days		5½ months	
		Percentage Hydrated	Depth of Hydration. See Table I	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns
	TRICALCIUM ALUMINATE																
19.06	No Calcium Sulfate Added............	.....	....	.....	...	79.1 79.2	3.82 3.90	...	....	89.67	5.09	.....	....	.....	....	.....	.....
22.20		.....	....	.....	....	79.78	4.58	.....	....	88.86	5.76	.....	....	.....	....	97.71	Complete
25.65		15.55	0.69	42.24	2.14	79.97	5.37	.....	....	87.42	6.39	.....	....	.....	....	.....	.....
22.20	1.6 per cent Calcium Sulfate added........	.....	....	.....	....	74.53	4.07	.....	....	87.12	5.49	.....	....	88.24	5.66	97.52	Complete
	Mean..................................	.....	0.69	.....	2.14	.....	4.35	.....	....	.....	5.68	.....	....	....	5.66	.....	.....
	Mixtures:																
23.64	10 per cent Calcium Ferro-aluminate....	.....	....	.....	....	85.56	5.62	.....	....	88.80	6.14	.....	....	.....	....	.....	.....
25.65	10 per cent Calcium Ferro-aluminate....	.....	....	.....	....	85.58	6.10	.....	....	90.37	6.94	.....	....	.....	....	.....	.....
	TRICALCIUM SILICATE																
25.20	No Calcium Sulfate added............	.....	....	.....	....	39.70	1.96	42.40	2.12	.....	....	76.80	4.76	75.10	4.68	.....	.....
21.86		.....	....	.....	....	58.60	2.13	.....	....	.....	....	74.70	3.47	.....	....	.....	.....
19.06		22.0	0.96	27.0	1.15	27.20	0.96	43.00	1.63	.....	....	.....	....	82.45	4.19	93.85[c]	5.77[c]
25.20	1.6 per cent Calcium Sulfate added........	.....	....	.....	....	.....	....	55.00	2.99	.....	....	74.75	4.74[a]	.....	....	.....	.....
	Mean..................................	.....	....	.....	....	.....	1.68	.....	2.25	.....	....	.....	4.32	.....	4.44	.....	.....
25.20	With 10 per cent Calcium Ferro-aluminate	.....	....	96.40	8.44	.....	....	99.30	10.19	.....	....	.....	....	.....	....	.....	.....
21.86		.....	....	94.45	6.76	.....	....	95.66	7.09	.....	....	.....	....	.....	....	.....	.....
25.20	With 33⅓ per cent Dicalcium Silicate....	.....	....	40.00	1.97	.....	....	26.70	1.24	.....	....	.....	....	.....	....	.....	.....
21.86		.....	....	35.6	1.49	.....	....	.....	....	.....	....	.....	....	.....	....	.....	.....

[a] 8 days. [b] 5 months. [c] 5½ months.

TABLE II.—(*Continued.*)

Mean Dimension, microns		1 minute		15 minutes		3 hours		24 hours		3 days		7 days		28 days		5½ months	
		Percentage Hydrated	Depth of Hydration. See Table I	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration, microns	Percentage Hydrated	Depth of Hydration microns	Percentage Hydrated	Depth of Hydration, microns
	DICALCIUM SILICATE																
18.09	No Calcium Sulfate added	.....	....	.....	....	.....	....	7.7	0.24	.....	....	14.0[a]	0.45	22.0	0.72	77.7	3.56
21.56	No Calcium Sulfate added	.....	....	.....	....	.....	....	7.6	0.28	.....	....	17.3[a]	0.66	20.7	0.80	73.8	3.88
18.09	1.6 per cent Calcium Sulfate added	.....	....	.....	....	.....	....	8.2	0.26	.....	....	21.2	0.69	29.8	1.01	.....	.....
21.56	1.6 per cent Calcium Sulfate added	.....	....	.....	....	.....	....	9.2	0.34	.....	....	17.7	0.68	21.5	0.79	71.6[b]	3.19
	Mean	.....	....	.....	....	.....	....	.....	0.28	.....	....	.....	0.62	.....	0.83	.....	3.54
	Mixtures:																
21.56	10 per cent Tricalcium Aluminate	.....	....	7.0	0.26	.....	....	66.9	3.33	.....	....	60.6[a]	2.88[a]	.....	....	.....	.....
21.56	10 per cent Calcium Ferro-aluminate	.....	....	.....	....	.....	....	.....	....	.....	....	44.3[a]	1.91[a]	.....	....	.....	.....
	SYNTHETIC PORTLAND CEMENT																
	Tricalcium Silicate............65 per cent Dicalcium Silicate............27 per cent Tricalcium Aluminate ....6 per cent Calcium Ferro-aluminate.......2 per cent (SiO_2 27.1 per cent, Al_2O_3 2.7 per cent, Fe_2O_3 0.7 per cent, CaO 69.5 per cent.)	....	....	27.4	1.19	.....	....	90.05	6.90	.....	....	.....	....	.....	....	.....	.....

[a] 8 days. [b] 5 months. [c] 5¾ months.

intermediate between the two silicates at ages up to seven days, as shown in Fig. 2.

In general, the mixtures of minerals reacted more rapidly with water than the single compounds. This was very marked whenever calcium ferro-aluminate was added. The mixture made up to approximate roughly commercial portland cement, and having an analysis as calculated of 27.1 per cent SiO_2, 2.7 per cent Al_2O_3, 0.9 per cent Fe_2O_3 and 69.3 per cent CaO; was nearly completely hydrated in 24 hours. Commercial portland cement clinker grains of similar size required several months to reach a similar degree of hydration.

Acknowledgment.—Grateful thanks are due R. H. Bogue of the Portland Cement Association Fellowship at the U. S. Bureau of Standards for supplying the minerals and to Mildred Staples for the painstaking and skillful counting of so many small particles.

DISCUSSION

Mr. L. T. Work[1]—We have carried out the first of a series of researches on the hydration of cement along somewhat similar lines to those described in the paper by Anderegg and Hubbell. We have measured the amount of free lime, as well as the amounts of free and combined water during the progress of aging. While it may be questioned as to just what state of combination those tests measure, at least in a relative sense they have shown that one of our high-early-strength cements showed more hydration in a short period of time—let us say 1 day or 7 days; that is, it had evolved more lime and it had combined with more water than was the case with a sample of ordinary cement of roughly equivalent fineness.

With respect to the element of fineness of the cement, we have tested cements of varying fineness from the same clinker to determine the amounts of free and combined water and free lime for different periods of aging. The fine cement reacted more completely than the coarse during the earlier period. The coarse cement reacted more slowly at first, but gradually approached the hydration of the fine cement at 6 months to 1 year. Yet at the end of that period, concrete samples which were made from that cement still had materially different strengths, that made from the fine cement being stronger.

So the question was raised in my mind as to whether this hydration of clinker subsequent to 7 or 28 days was really so vital, or whether the hardening processes which took place in cement were rather those of crystallization than those of subsequent hydration of the clinker.

Mr. N. C. Johnson.[2]—It seems to me that in some of these swift hydrations we are suffering from over hydration amounting to hydrolysis. I should like to ask Mr. Anderegg if he made any observation of hydrolysis in very fine ground cements.

Mr. F. O. Anderegg.[3]—With regard to the fineness of grinding, there is a geometric law for the distribution of particles of different sizes giving two or three gradings, which will produce the best pack-ing. The size distribution of the cement is going to be nearly as important in the fine grinding as is the question of the rate of hydration. For instance, we have taken a cement, which as commercially ground would give about 700 lb. per sq. in. compressive strength at 24 hours and have separated this cement into fractions and recombined according to certain definite designs, in just the way you would combine sized sand or gravel to get any desired grading, and we have been able to get 2500 lb. per sq. in. compressive strength at 24 hours with this same clinker, using the best size distribution. Of this, about 25 per cent was below 10 microns and then it graded on up. Incidentally, this particular grading that gave the best results was a logarithmic grading; that is, if you plot the logarithm of the size of the particle against the cumulative percentage, you get a straight line. That means, of course, more fine material than is usually found in commercial cements.

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[1] Assistant Professor of Chemical Engineering, Columbia University, New York City.

[2] Concrete Surface Corporation, New York City.

[3] Senior Industrial Fellow, Mellon Institute of Industrial Research, Pittsburgh, Pa.

The absorption of specimens prepared in this way was of the order of 1.5 per cent after 24 hours of soaking.

In regard to the hardening processes, we have worked with cement flour, practically all of which was completely hydrated within 24 hours, and found that it is that cement which hydrates first or hydrates early in the game, that contributes to the increase in strengh developed in the cement. Flour separated from high-early-strength cement gave about 5500 lb. per sq. in. compressive strength in 1 day, and reached above 8000 lb. in one year.

With regard to Mr. Johnson's question, I have made no attempt to do anything on hydrolysis of the cements after hydration. That is being ably handled at the Bureau of Standards and I have devoted my attention to other things. However, the amount of water present has a great deal to do with the hydrolysis and if the surface area to be wet is proportionate to the amount of mixing water, the hydrolysis should be nearly constant.

MR. P. H. BATES.[1]—I wonder if Mr. Anderegg will tell us, when he increased the strength from 700 to 2500 lb. per sq. in., what type of specimen he used.

MR. ANDEREGG.—Naturally, the amount of material available for this type of work is limited, and we used 1-in. cubes and mechanical tamping. The mix was 1:3, using standard Ottawa sand.

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[1] Chief, Clay and Silicate Products Division, U. S. Bureau of Standards, Washington, D. C.

A STUDY OF FOURTEEN BRANDS OF STANDARD PORTLAND CEMENTS AND FOUR EARLY-STRENGTH CEMENTS

BY C. H. SCHOLER[1] AND L. H. KOENITZER[2]

SYNOPSIS

The trend of concrete investigation in the past few years has been towards a critical study of cements and their concrete-making qualities. Such a study was undertaken last winter by the Engineering Experiment Station of the Kansas State College through its Road Materials Laboratory, the official laboratory of the Kansas Highway Commission, to determine the variations between the brands of cement in use in this territory as found in the properties that might affect their concrete-making qualities.

The properties studied were the standard chemical and physical properties, the compressive and flexural strengths in mortar and concrete, the workability or consistency as expressed by slump and flow, the water-cement ratio - strength relation for each cement through a narrow range, and the mortar voids characteristics of each of the eighteen brands of cement studied.

While certain well-defined characteristic differences seem to be brought out by this study, the general impression from the data is that of rather unusual uniformity. The data indicates that the peak of the water-cement ratio - strength relation is much broader for some brands than for others. The quantity of water required to produce maximum density (basic water content) varied but little for most of the brands studied, the maximum variation shown being 20 per cent between the high and the low values.

INTRODUCTION

There is a wide-spread interest at the present time in the study of the characteristics of cements. Committee C-1 on Cement of this Society gave a report on thirty-two brands of cements at the 1928 annual meeting of the Society.[3] Only two or three of the brands of cement reported in this paper were included in the report of Committee C-1. Practically every brand of cement reported herein was used on highway construction work in Kansas during the past year. These cements were manufactured in Kansas or adjoining states and were made of materials from very similar geological formations.

The question has often been raised whether certain brands of cements have certain characteristics which makes one brand of cement more desirable than another. A study of different brands of cements

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[2] Instructor in Applied Mechanics, Kansas State Agricultural College, Manhattan, Kans.

[3] *Proceedings*, Am. Soc. Testing Mats. Vol. 28, Part I, p. 233 (1928).

TABLE I.—CHEMICAL ANALYSES OF FOURTEEN STANDARD PORTLAND CEMENTS AND FOUR EARLY-STRENGTH CEMENTS.

Each value reported is the average of two individual analyses by an experienced chemist.

Brand of Cement	SiO_2, per cent	Fe_2O_3, per cent	Al_2O_3, per cent	R_2O_3, per cent	CaO, per cent	MgO, per cent	SO_3, per cent	Loss on Ignition, per cent	Insoluble Residue, per cent	$\frac{SiO_2}{R_2O_3}$	$\frac{Al_2O_3}{Fe_2O_3}$	$\frac{CaO}{SiO_2 + R_2O_3}$	3 CaO Al_2O_3,[a] per cent	2 CaO Fe_2O_3,[b] per cent	$CaSO_4$,[c] per cent
STANDARD PORTLAND CEMENTS:															
A...........	22.12	1.88	6.82	8.70	64.32	3.04	1.71	0.70	0.31	2.54	3.63	2.09	18.07	3.20	2.91
B...........	20.44	2.72	6.78	9.50	63.90	1.89	2.09	1.49	0.29	2.15	2.49	2.13	17.97	4.62	3.55
C...........	22.51	2.84	6.03	8.87	64.84	1.22	1.42	1.52	0.40	2.54	2.12	2.07	15.98	4.83	2.41
D...........	21.17	3.56	5.78	9.34	63.84	2.94	1.59	0.79	0.33	2.27	1.62	2.09	15.32	6.05	2.70
E...........	21.67	2.96	5.89	8.85	64.12	3.00	2.01	0.82	0.18	2.45	1.99	2.10	15.61	5.03	3.42
F...........	20.67	2.68	7.66	10.34	64.73	1.78	1.71	1.54	0.22	2.00	2.86	2.09	20.30	4.56	2.91
G...........	21.96	2.24	6.11	8.35	64.78	1.59	1.80	1.86	0.26	2.63	2.73	2.14	16.19	3.81	3.06
H...........	21.99	2.84	5.83	8.67	64.17	2.06	1.78	1.76	0.33	2.54	2.05	2.09	15.45	4.83	3.03
I...........	21.44	3.18	6.64	9.82	64.38	2.55	1.76	0.91	0.12	2.18	2.09	2.06	17.60	5.41	2.99
J...........	21.16	2.92	5.97	8.89	65.66	2.55	1.38	0.94	0.14	2.38	2.04	2.19	15.82	4.96	2.35
M...........	21.78	2.68	5.93	8.61	63.15	3.85	1.78	1.13	0.39	2.53	2.21	2.08	15.71	4.56	3.03
S...........	22.39	2.69	6.25	8.94	64.09	2.06	1.78	1.18	0.30	2.50	2.32	2.05	16.56	4.57	3.03
W...........	21.61	1.88	7.93	9.81	65.04	1.79	1.63	0.62	0.17	2.20	4.22	2.07	21.01	3.20	2.77
X...........	21.64	2.74	6.37	9.11	64.69	2.84	1.77	0.40	0.16	2.38	2.32	2.10	16.68	4.66	3.01
HIGH-EARLY STRENGTH CEMENTS:															
N...........	7.29	16.24	33.58	50.82	37.74	1.68	0.63	1.52	5.52	0.14	2.07	0.65	......	.....	2.96
P...........	20.18	3.42	4.75	8.17	65.92	2.61	1.74	1.23	0.24	2.47	1.39	2.33	12.59	5.81	2.96
T...........	17.76	2.80	9.48	12.28	65.49	1.39	2.19	1.69	0.28	1.45	3.39	2.18	25.12	4.76	3.74
Z...........	20.26	2.16	6.24	8.40	67.03	1.24	2.27	0.69	0.25	2.41	2.89	2.34	16.54	3.67	3.86

[a] 2.65 × Al_2O_3 = 3 CaO Al_2O_3.

[b] 1.70 × Fe_2O_3 = 2 $CaOFe_2O_3$.

[c] 1.70 × SO_3 = CaSO.

TABLE II.—RESULTS OF PHYSICAL TESTS OF FOURTEEN STANDARD PORTLAND CEMENTS.

All tests made in accordance with A.S.T.M. Standards.
Each value reported is the average of twelve values determined by three experienced cement testers.

Brand of Cement	Time of Set (Gilmore Needle)				Normal Consistency, per cent of Water	Fineness, per cent Passing No. 200 Sieve	Flour,[1] per cent	Specific Gravity at 70° F.	Tensile Strength, 1:3 Ottawa Sand Mortar, lb. per sq. in.		Compressive Strength, 1:3 Ottawa Sand Mortar, 2 by 4-in. Cylinder, lb. per sq. in.	
	Initial		Final									
	min.	sec.	min.	sec.					7 days	28 days	7 days	28 days
A.......	3	55	6	25	24.0	18.37	45.0	3.14	287	388	2450	3961
B.......	3	42	5	55	23.5	14.27	48.0	3.16	305	362	2583	3853
C.......	4	12	7	00	24.0	12.57	51.0	3.13	294	426	2877	4628
D.......	4	07	7	15	23.5	13.03	49.5	3.16	310	420	2456	4875
E.......	4	15	6	45	23.0	13.97	48.5	3.15	329	441	2633	4283
F.......	4	35	6	55	24.0	11.26	53.0	3.15	328	454	3511	4567
G.......	3	25	6	25	23.5	11.62	50.0	3.10	315	426	3117	4283
H.......	4	03	6	22	23.0	13.69	49.0	3.15	329	445	2700	3867
I.......	4	00	6	48	23.5	13.23	47.0	3.15	344	420	2989	4111
J.......	4	40	6	40	23.5	11.07	50.0	3.21	317	404	3025	3839
M.......	3	50	6	15	23.8	8.82	53.0	3.15	361	425	2931	4322
S.......	4	18	7	00	23.3	10.35	49.0	3.14	284	387	2472	3722
W.......	3	55	6	10	23.6	10.70	54.0	3.13	347	451	3139	4694
X.......	4	10	6	48	23.6	15.93	43.0	3.13	311	397	2688	4083

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[1] The authors are indebted to Mr. Geoff. A. Saeger, Chemical Engineer, Missouri Portland Cement Co. for the flour tests.

over a period of years indicates that the concrete-making qualities of each brand of cement might be different. In actual paving construction work, inspectors have noted a difference in the amount of water required for different brands of cements, as well as a difference in the workability of the cements. The work done during this investigation was based primarily upon highway uses and requirements.

This paper presents data on: the relationship between the chemical ingredients of each brand of cement; time of set, normal consistency, fineness and specific gravity of the cements; slump and flow tests; density of mix; tensile and compressive strengths of mortars; and flexural and compressive strengths of concrete.

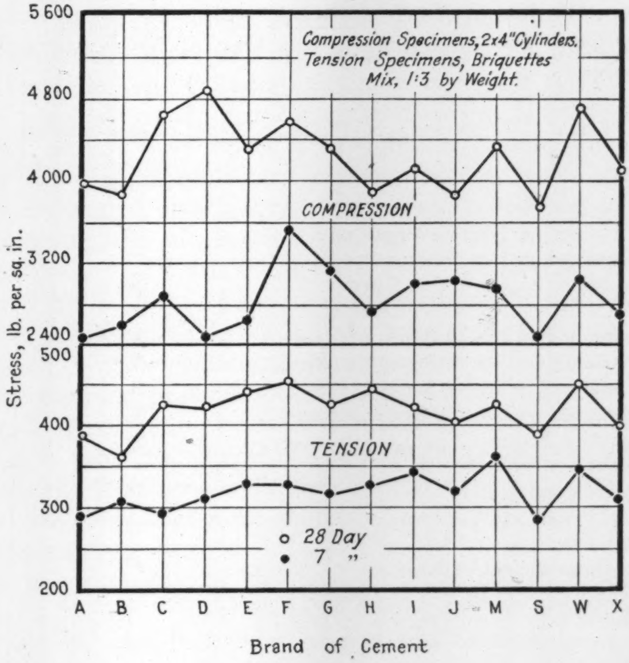

FIG. 1.—Tension and Compression Tests of Ottawa Sand Mortars of 14 Brands of Portland Cements.

MATERIALS

Cement.—Three sacks of cement were received from each mill cooperating in the research. The three sacks were mixed together and placed in galvanized cans with tight-fitting lids. Chemical analyses and physical tests of the cements are given in Tables I and

II. The tensile and compressive strength of 1:3 Ottawa sand mortars given in Table II are shown graphically in Fig. 1.

Aggregate.—The sand was secured locally from the Kansas River. It was a well-graded material with a gradation of 2.68 (fineness modulus). The coarse aggregate in this experiment was durable sandstone secured from Lincoln, Kans. The sandstone was well graded from 1½ to ¼ in. in size, weighing 89.9 lb. per cu. ft. Properties of the aggregates are recorded in Table III.

Mixing Water.—The water used in mixing the concrete was secured from the Kansas State College supply which is used for drinking purposes. The mixing water was kept at 70° F. throughout the experiment.

TABLE III.—RESULTS OF PHYSICAL TESTS OF AGGREGATES.

	LINCOLN SANDSTONE	KANSAS RIVER SAND
SIEVE ANALYSIS:		
Retained on ¾-in. Sieve, per cent	72	0
Retained on ⅜-in. Sieve, per cent	97	0
Retained on No. 4 Sieve, per cent	100	0
Retained on No. 8 Sieve, per cent	100	6
Retained on No. 14 Sieve, per cent	100	20
Retained on No. 28 Sieve, per cent	100	48
Retained on No. 48 Sieve, per cent	100	94
Retained on No. 100 Sieve, per cent	100	100
Gradation Factor	7.69	2.68
Weight per cubic foot, lb.	89.9	109.8
Specific gravity	2.65	2.62
Loss by washing, per cent	.....	0
Color test	.....	Clear
French coefficient of wear	8.7	
Strength ratio in tension at 28 days		160
Strength ratio in compression at 28 days		113

TESTS OF MORTARS AND CONCRETES

Slump and Flow Tests:

Two experienced concrete operators made all slump and flow-table tests. The Society's Tentative Method of Test for Consistency of Portland-Cement Concrete (D 138 – 26 T) was followed in the slump tests. The flow was determined on a 28-in. aluminum table, using a truncated cone 6¾ in. in diameter at the top, 10 in. in diameter at the bottom, and 5 in. high. The table was raised ½ in. and dropped 15 times in 15 seconds. Several of the drier mixes gave a crumbling and not a flowing action. In such a case the flow was recorded as 100 (that is, no flow) for that particular mix.

The slump and flow tests of the different brands of cements show a definite relationship between slump and flow. The correlation factor was found to be 0.86, which is good.

Mortar-Void Study:

A mortar-void study was made by three operators on each brand of cement. A local river sand was used. All materials were weighed in metric units on an accurate torsion balance. The mix used was 1:3½ by absolute volume, which is practically equivalent to a 1:3 mix by weight for average materials.

After the specific gravities of the different sands and cements were determined, the proportion was calculated and a mix of sufficient size for one 3 by 6-in. cylinder was made up. In a typical case, the operator weighed out 563 g. of cement and 1640 g. of local sand. The sand and cement were mixed thoroughly by rolling the materials together in a piece of oil cloth 1 yd. square, after which the dry materials were poured into a square galvanized pan 28 by 28 by 4 in. In determining the basic water content of this mix, the operator added to the dry mix 170 cc. of water from a burette. The mortar was mixed by hand for 1½ minutes, after which the operator filled a 3 by 6-in. cylinder mold, placing the mortar in the mold in three layers, each layer being tamped twenty times with a tamper ¾ in. in diameter, tamping head about 1 in. long, total weight about 1 lb. The molds were made of seamless tubing split down the side and machined to constant volume. The recorder did all the weighing of the molds and specimens while the operator weighed all materials and did all the mixing. After the mold was weighed the operator dumped the materials back into the pan and added 10 cc. of water. The material was remixed and the mold filled the second time. If the material in the mold weighed more the second time than it did the first, it was dumped back into the pan and another 10 cc. of water was added. It required ten to fifteen minutes to make three tests on one batch of material. The third batch usually showed a dropping off in weight, indicating that the maximum density had been passed.

The operator then made another batch of the same materials, using the same weights and adding 5 cc. less water than was required to give the densest mix. After mixing for 1½ minutes, the mold was filled and the weight determined. The material was then dumped back into the pan, 5 cc. of water was added and the process repeated. A third batch of material was then weighed up and the amount of water added which gave the highest weight. If this batch gave the same weight as that obtained in the preceding batch for the same amount of water, the basic water content was considered determined.

TABLE IV.—RESULTS OF MORTAR-VOID STUDIES, SHOWING RELATIONSHIP BETWEEN WATER-CEMENT RATIO, DENSITY, CONSISTENCY AND STRENGTH OF MORTARS.

Proportions: 1 part cement to 3½ parts local sand by absolute volume.
Each value is the average of five tests.

Brand of Cement	Ratio of Water Content to Basic	Water-Cement Ratio	Density	Consistency		Compressive Strength of 3 by 6-in. Cylinders, lb. per sq. in.	
				Slump, in.	Flow	7 days	28 days
STANDARD PORTLAND CEMENTS							
A	0.8	0.444	0.7365	0	100	2652	3800
	1.0	0.553	0.7506	0	100	3090	5158
	1.2	0.664	0.7431	0.5	147.5	2773	5070
	1.4	0.775	0.7209	6.75	217.5	2622	4783
B	0.8	0.391	0.7525	0	100	2652	3071
	1.0	0.489	0.7927	0	100	3995	5498
	1.2	0.586	0.7741	0.5	120	3636	5487
	1.4	0.684	0.7368	1	150	2571	3645
C	0.8	0.435	0.7647	0	100	3616	4199
	1.0	0.540	0.7836	0	100	4004	5617
	1.2	0.648	0.7522	2	190	3557	5523
	1.4	0.756	0.7290	5.5	210	2838	5325
D	0.8	0.433	0.7565	0	100	3178	4116
	1.0	0.540	0.7807	0	100	3626	5165
	1.2	0.648	0.7589	1	170	3586	5443
	1.4	0.754	0.7298	6.5	202.5	2563	4802
E	0.8	0.407	0.7428	0	100	2870	3007
	1.0	0.508	0.7741	0.063	100	3675	4251
	1.2	0.610	0.7596	0.5	137.5	3458	4676
	1.4	0.712	0.7331	2.75	195	2987	4720
F	0.8	0.392	0.7431	0	100	2718	3463
	1.0	0.484	0.7461	0	100	3227	3982
	1.2	0.586	0.7678	0.625	130	4848	5377
	1.4	0.683	0.7460	6.5	197.5	4295	5326
G	0.8	0.434	0.7506	0	100	3073	3185
	1.0	0.540	0.7704	0	100	3177	4951
	1.2	0.648	0.7502	0.5	150	2822	5055
	1.4	0.754	0.7300	7	210	2690	4837
H	0.8	0.450	0.7322	0	100	2460	3240
	1.0	0.562	0.7607	0	100	2964	4197
	1.2	0.675	0.7366	2	150	2724	4850
	1.4	0.787	0.7202	8.5	230	2101	3593
I	0.8	0.444	0.7336	0	100	2977	3662
	1.0	0.553	0.7592	0	100	3452	5139
	1.2	0.664	0.7399	1.25	165	3528	5170
	1.4	0.775	0.7248	7.75	250	3132	5277
J	0.8	0.434	0.7371	0	100	3001	3422
	1.0	0.540	0.7675	0	100	3472	4977
	1.2	0.648	0.7398	1.375	182.5	3202	4573
	1.4	0.754	0.7320	2	202.5	2912	4568
M	0.8	0.407	0.7300	0	100	2540	2722
	1.0	0.508	0.7657	0	100	3377	4715
	1.2	0.611	0.7524	1	145	3743	4949
	1.4	0.712	0.7363	6.5	205	3392	5129
S	0.8	0.411	0.7213	0	100	2353	2506
	1.0	0.514	0.7593	0	100	3399	4013
	1.2	0.617	0.7536	0.5	130	3505	4570
	1.4	0.720	0.7323	6	200	2812	4659
W	0.8	0.434	0.7594	0	100	1998	3107
	1.0	0.540	0.7713	0	100	4618	5871
	1.2	0.648	0.7560	1	144	4932	6187
	1.4	0.754	0.7348	8.5	237.5	3924	5846
X	0.8	0.411	0.7146	0	100	2230	2433
	1.0	0.514	0.7593	0	100	3218	3932
	1.2	0.617	0.7480	0.75	141.25	2911	4180
	1.4	0.720	0.7365	6.5	210	2832	4495

TABLE IV.—*Continued.*

Brand of Cement	Ratio of Water Content to Basic	Water-Cement Ratio	Density	Consistency		Compressive Strength of 3 by 6-in. Cylinders, lb. per sq. in.	
				Slump, in.	Flow	7 days	28 days
EARLY-STRENGTH CEMENTS							
N	0.8	0.414	0.7422	0	100	3626	3746
	1.0	0.514	0.7802	0	100	5870	6348
	1.2	0.617	0.7653	2	167.5	6157	6901
	1.4	0.720	0.7522	8.5	256.2	5920	7205
P	0.8	0.401	0.7365	0	100	2147	2679
	1.0	0.502	0.7652	0.125	100	2779	4045
	1.2	0.602	0.7563	0.375	136.2	2440	3860
	1.4	0.702	0.7380	Not recorded		1600	2742
T	0.8	0.401	0.7370	0	100	2439	2441
	1.0	0.502	0.7801	0	100	3328	3727
	1.2	0.602	0.7649	0.875	142.5	2738	3291
	1.4	0.702	0.7352	4.5	210	2025	2966
Z	0.8	0.416	0.7338	0	100	2549	3489
	1.0	0.527	0.7812	0.125	115	3419	4832
	1.2	0.633	0.7517	2.25	187.5	1917	4994
	1.4	0.738	0.7349	8.5	252.5	1405	3290

The basic water content may vary as much as 3 per cent when the same operator tries to check himself later. Different operators get slightly different results, varying as much as 5 per cent of water, although they get practically the same kind of a curve for the different cements.

After the basic water content was determined, the same operator mixed up four batches of mortar for each cement, each sufficient to make ten 3 by 6-in. cylinders. In the first batch, sufficient water was added to the dry mix to give an equivalent water content of 0.8 of the basic water content. The second batch was basic water content, the third 1.2 basic, and the fourth batch 1.4 basic. Before the cylinders were made, flow and slump tests were made on the mortar. The cylinders were numbered in consecutive order and tested in compression at 7 and 28 days, the odd numbers being broken at the age of 7 days and the even numbers at the age of 28 days, making five specimens of each water content for each cement tested at each age. The specimens were tested in an Olsen 100,000-lb. testing machine, the load being applied at the rate of 0.05 in. per minute. A special 3-in. spherical top bearing was used.

The data are presented in Table IV. Typical graphs showing the relation of density and water-cement ratio to compressive strength are shown in Figs. 2 and 3.

Flexure and Compression Tests of Concrete:

After the basic water content of the mortar for each brand of cement was determined, a concrete mix 1:1.8:3.2 by volume—a

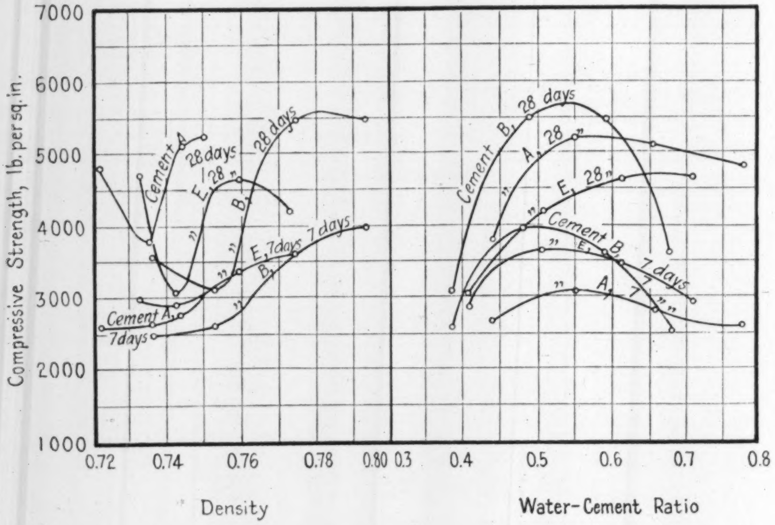

FIG. 2.—Density, Water-Cement Ratio and Strength Characteristics of Standard Portland Cements A, B and E.

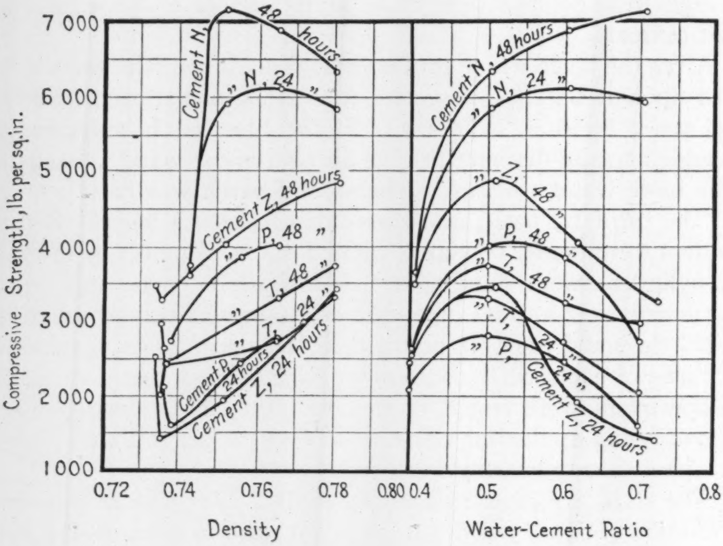

FIG. 3.—Density, Water-Cement Ratio and Strength Characteristics of Four High-Early-Strength Cements.

typical paving mixture—was made up using an amount of water equivalent to 1.3 times the basic water content of the mortar. Two 6 by 6 by 35-in. beams were made from each brand of cement. Enough concrete for both beams was mixed in a power mixer for two minutes at 18 r.p.m. The concrete was placed in the molds in 3-in. layers, and each layer was tamped 120 times with a $\frac{5}{8}$-in. rod having a bullet-pointed end. Two cutting strokes were made on each side of the specimen with a brick trowel. The beams were covered with moist burlap for the first 24-hours, then removed from the molds and stored in the moist room, which was maintained at 70° F. and practically 100 per cent humidity. The weight per cubic foot of concrete remained very constant, which was an indication that the different water-cement ratios were giving practically the same density in the specimens.

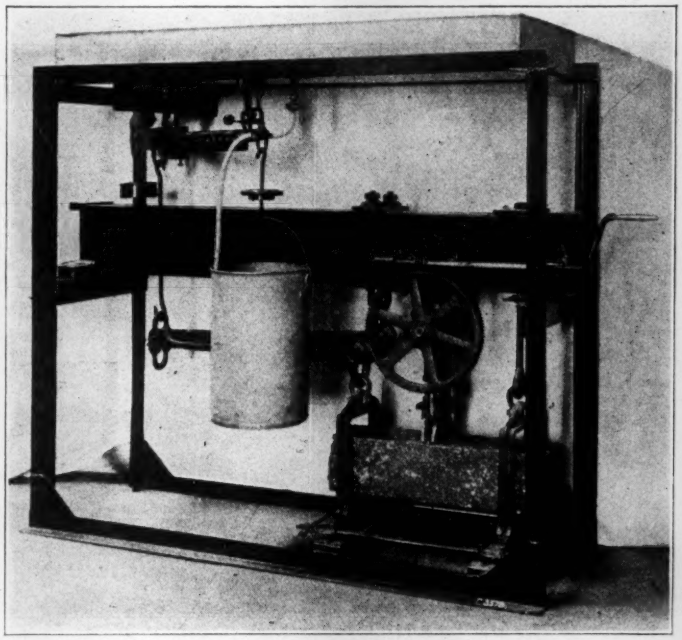

FIG. 4.—Field Concrete Beam Testing Machine.

The beams were tested in a field beam testing machine illustrated in Fig. 4, perfected by the Materials Department of the Iowa State Highway Commission. Several states have one of these testing machines on each paving job in these states. The machine is portable. It also fits into a small space, permitting it to be placed in the average field inspector's laboratory. The load is applied on the top of the beam midway between supports by turning a crank attached to a worm gear on the jack. One principle of this machine approaches the ideal in that the load is applied at a constant uniform rate. Water from the reservoir on top of the machine passes through a rubber hose underneath the scale beam into a bucket hooked on to the end of the scale beam. By keeping the scale beam balanced the load is applied at a uniform rate. When the specimen breaks in flexure, the scale beam drops on the rubber hose, cutting off the water supply. The load is determined by weighing the bucket and water on the end of the lever connection and multiplying by 100 (ratio of the levers). The breadth and depth of the specimen at the break is measured to the closest 0.02 in.

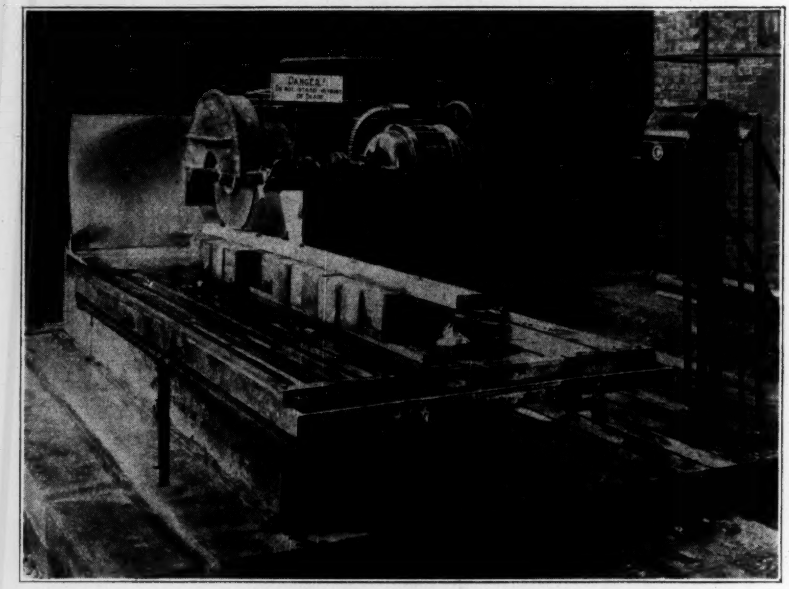

FIG. 5.—24-in. Carborundum Saw.

After the beams were tested, the ends were sawed square on a 24-in. carborundum saw, illustrated in Fig. 5, run by a 30-h-p. electric motor turning at the rate of 1200 r.p.m. A small electric motor moves the table back and forth at a constant speed. The specimens were then capped with plaster-of-Paris and tested in compression in a 300,000-lb. Riehle testing machine.

The results of the flexure and compression tests are summarized in Table V, which gives also the water-cement ratio, slump and flow, weight per cubic foot and yield of the concretes from both standard portland cements and high-early-strength cements. Modulus of rupture and compressive strength for the standard cement concretes are shown in Fig. 6.

DISCUSSION AND CONCLUSIONS

The authors make no attempt to draw any conclusions from the results of the chemical analyses or their relation to the physical properties. Of the standard physical tests it will be noted that the percentage of flour follows very closely the percentage passing the No. 200 sieve.

TABLE V.—RESULTS OF TESTS OF CONCRETE.

Proportions: 1:1.8:3.2 by volume.
Values of modulus of rupture are the average of two tests.
Values of compressive strengths are the average of four tests.

Brand of Cement	Water-Cement Ratio	Slump, in.	Flow	Weight, lb. per cu. ft.	Yield, bbl.	Modulus of Rupture, lb. per sq. in.		Compressive Strength at 28 Days, lb. per sq. in.
STANDARD PORTLAND CEMENTS								
						7 days	28 days	
A	0.689	1	120	150.4	1.610	441	600	4611
B	0.625	4.75	170	148.6	1.576	458	604	3701
C	0.693	3.5	130	149.6	1.607	513	637	4957
D	0.693	3.5	155	151.0	1.620	468	552	4243
E	0.693	1	137.5	148.4	1.594	563	675	3694
F	0.639	1.25	110	150.6	1.626	525	626	4604
G	0.734	1.5	115	149.0	1.595	457	572	4245
H	0.725	3	120	145.4	1.557	359	532	3556
I	0.734	5.375	140	150.0	1.605	437	571	3889
J	0.697	1.75	120	149.6	1.605	452	607	4333
M	0.655	2	140	148.4	1.600	458	587	4278
S	0.663	3	125	151.4	1.627	497	622	4042
W	0.693	2	140	148.0	1.590	538	613	3772
X	0.663	2.75	135	148.8	1.603	474	557	3384
EARLY-STRENGTH CEMENTS								
						24-hr.	48-hr.	
N	0.663	3	130	149	1.606	639	751	6143
	0.700	6	135	150.2	.....	615	578	4555[a]
P	0.686	1.5	125	148.2	1.593	334	493	4516
	0.700	4	185	146	.....	283	439	4144[a]
T	0.698	2	125	150	1.618	402	612	5364
	0.700	3.5	155	148.8	.....	302	460	4578[a]
Z	0.670	2.25	135	149.2	1.605	370	602	4552
	0.700	3.5	150	149	.....	230	497	4552[a]

[a] Compressive strength at 14 days.

The normal-consistency determination for these cements varied but little and the operators following the specified methods closely were able to get consistent checks. It was observed, however, that there was a very marked variation in the consistency of the standard mortars when made up using the quantity of water indicated by the normal consistency. It is the opinion of the authors that the determination of normal consistency is of doubtful value for indicating the quantity of mixing water to be used.

It will be noted that the maximum density of a mortar did not give the maximum strength in every case.

The tension and compression tests of the cement mortars show uniformly satisfactory results in general accord with each other.

The flexural strengths of the concrete were fairly uniform, whereas the compressive strengths showed a wide variation (Fig. 6). Several brands of cement that gave the higher flexural strengths gave the lower compressive strengths.

The slump and flow tests of the mortar and the concrete show generally good agreement, with some outstanding exceptions. Cement B gave low slump and flow in the mortar tests, and high values in the concrete tests. Cement A gave much more slump and flow than did cement B, but at a low water content in the mortar; cement B shows more workability than cement A, but not to a large extent.

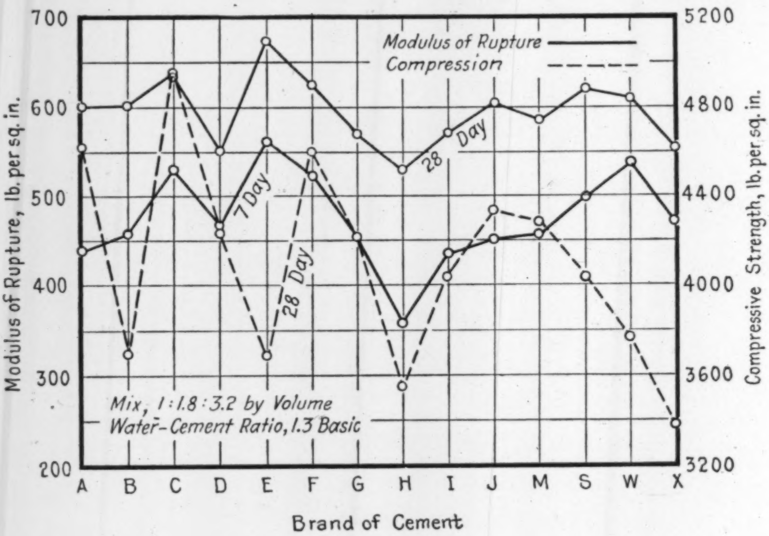

FIG. 6.—Flexure and Compression Tests of Concrete from 14 Brands of Portland Cements.

Similar comments could be made on some of the other inconsistencies. The relationship between slump and flow is very good from the point of view of statistical analysis, but the authors believe that the slump test is simpler and more fool-proof and easier to make and interpret in terms of field conditions. Neither one is at all capable of measuring the finer distinctions of plasticity and workability. It has long been the authors' opinion that these factors cannot be expressed in terms of one measure.

The chief variation in the various brands studied seems to be to their sensitivity to small variation in water content in the mortar mixes at basic water content and above. Some cements showed in this investigation but little loss in strength with added water content, while others show a very sharp decline in strength. The extent of this investigation is not sufficient to determine whether the variations shown are characteristic of the respective brands, but some field data very definitely confirm this for mortar concretes. Additional cement of the brands showing the most markedly different characteristics are being secured for further study, which should definitely show the extent of this variation and whether or not it is a distinct characteristic.

The concrete tests using a typical paving mixture gave satisfactory results in every case. The water content chosen was 1.3 times the basic value given by the mortar tests. The resulting concrete showed a wide variation in workability as measured by the slump and flow tests. The mortar voids characteristics were determined for a mix 1:3.5 by absolute volume. Had this determination been made upon a mix more nearly fitting the mortar used in the paving mixture, it is probable that a more uniform consistency would have been secured. The flexure test gave satisfactory values in every case, with a maximum variation between high and low values of about 26 per cent. The compressive strength of the same concrete (tests of beam ends) varied by 47 per cent between high and low values, with the beams strongest in flexure showing in some cases the lower values in compression. No explanation is given for this variation and the number of tests is not sufficient to draw conclusions.

In spite of the rather wide variations that are shown in some instances, the uniformly satisfactory values given are very interesting. Wide as the variations are, they are no greater than would be found between an equal number of laboratories working on identical samples. It is the authors' judgment that until laboratory and field technique has been developed much more thoroughly than at present, the engineering profession is not in a position to discriminate very closely between brands of cement as similar in their properties as those covered in this investigation.

The authors have restricted their conclusions to the standard portland cements. Of the early-strength cements, three were portland cements and one was a high-alumina cement. The early-strength cements seemed to be more plastic and workable than the normal portland cements. The high-alumina cement required water in considerable excess of basic to give the maximum strength in the mortar mix.

DISCUSSION

MR. J. C. PEARSON.[1]—There are two simple questions I should like to ask the authors. The first one is, how do they define flour in cement and what kind of apparatus was used to determine the flour.

On the percentage relationship expressed in the flour content, it is quite probable that the micron sizes are in the neighborhood of 40, and for the sake of clarity it would seem that that should not be considered as flour. That is a rather coarse material.

The second question is in regard to the sand in the mortar-void tests, whether the absorption was known and whether it was allowed for in those tests.

MR. L. H. KOENITZER.[2]—I can give very little information on the test for per cent of flour, because we sent the samples to Mr. Saeger, Chemical Engineer of the Missouri Portland Cement Co., and he made the tests. A comparison of the air analyzer used by Mr. Saeger with those of other laboratories indicates the flour is 35 microns and under.

In regard to the local sand used, we ran a number of tests on absorption, and we were unable to find any absorption.

MR. H. F. GONNERMAN.[3]—I should like to ask the authors what methods were used in preparing the ends of the compression specimens. It seemed to me there is quite a discrepancy between the results of the flexure and compression tests shown in Fig. 6.

MR. KOENITZER.—The specimens are 6 by 6-in. prisms capped with plaster of Paris. These were capped on a machined steel plate, and there was a very smooth surface. We put on a very thin coat of plaster of Paris. I do not think that the variation in compressive strengths could be laid to the capping of the specimens. Something entered in there but we do not know how to account for it.

MR. L. W. TELLER.[4]—I should like to ask the authors what knowledge they have of the moisture condition of these specimens at the time they were tested. In the Bureau of Public Roads we have done some work with sawed beams and it has been our experience that the sawing process requires a great deal of water and the beam is pretty well saturated by the time we get through sawing it out. Unless we take pains to dry these specimens out and put them in a uniform condition of moisture, we get undue variations in the flexural strengths. I thought possibly that something of that kind would account for some of the variations in strength of the specimens mentioned by the author.

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[1] Assistant to Chemical Engineer, Lehigh Portland Cement Co., Allentown, Pa.

[2] Instructor in Applied Mechanics, Kansas State Agricultural College, Manhattan, Kans.

[3] Manager, Research Laboratory, Portland Cement Assn., Chicago, Ill.

[4] Senior Engineer of Tests, U. S. Bureau of Public Roads, Washington, D. C.

MR. KOENITZER.—In answer to this question, we made a determination of the moisture of the compression test specimens, and found the moisture content to be quite uniform.

MR. P. H. BATES.[1]—There is one statement that the authors make that I am afraid I cannot agree with when I look at the data, and that is, " . . . the engineering profession is not in a position to discriminate very closely between brands of cement as similar in their properties as those covered in this investigation." In the preceding paragraph the statement appears: "The resulting concrete showed a wide variation in workability as measured by the slump and flow tests." I quite agree with the authors in their statement that the slump and flow tests are not a measure of workability, but what they do bring out in that particular paragraph is the fact that in this ordinary way as the fellow around the job looks at concrete there was a wide difference in the concrete, and it happens to be one of those wide differences which the engineer does take into consideration and does discriminate very closely.

I further agree with the authors that if the engineer is making use of the results from the different laboratories he possibly is not justified in discriminating between the results as given here in trying to decide which brand to use. But, on the other hand, if the engineer does make all his tests at one laboratory, I wonder whether he cannot discriminate between them and whether he would not discriminate between them.

In the matter of yield I notice according to the data the variation is about 8 per cent, and I believe to any engineer, and a contracting engineer, an 8-per-cent difference in yield is extremely intriguing when he figures his cost.

Then if we take the question of water-cement ratio *versus* strength, we find quite marked differences in the data presented in Table V. I notice also that in Table V there are two cements indicated that did have the same high water-cement ratio, and when I compare these with the one which required the minimum water I find that the latter gave a very high flow. In the field, this is certainly something again that a discriminating engineer would make use of and would be quite a factor influencing him if he wanted to discriminate between brands. On the whole, I do not feel that the cited statement is justified by the data, although I agree with the authors that between laboratories they probably would not be justified in discriminating. But ordinarily an engineer when he is trying to discriminate between brands does not parcel out his work around a group of laboratories but has it all done in one.

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[1] Chief, Clay and Silicate Products Division, U. S. Bureau of Standards, Washington, D. C.

MR. C. H. SCHOLER.[1]—Replying to two of the questions that have been raised, I think that Mr. Teller's question has not been answered, as he stated it. He was inquiring whether or not the 6 by 6 by 12-in. prisms that we tested were in the same condition of moisture content.

MR. TELLER.—My questions were: First, was the moisture content of the prisms uniform at the time of test; second, was the moisture content of the cylinders uniform at the time of test; and, third, were the variations in the compressive strength of the specimens tested immediately after the flexural test about the same as those of the specimens which were stored in the laboratory?

MR. SCHOLER.—The moisture content of the cylinders that were tested should have been the same. They were all stored in a moist room under identical conditions until the time of test. The moisture content of the prisms might not have been quite the same but they were all kept in the moist room until the time of test. As the beam was broken in flexure at 28 days, the pieces were immediately taken to the carborundum saw and the ends sawed square, and they were capped and tested. Now the moist room is a very efficient moist room, and there is no question but that everything was in a thoroughly saturated condition at all times in the room, but there might have been some change in the water content at the time they were broken in flexure and sawed in the saw. There is something unseemly that has occurred on those specimens.

Replying to Mr. Bates' question as to whether or not engineers should discriminate between cements varying as closely as they do, I would say that if we had as good control of our construction projects as we have of our laboratories we would try to take advantage of those conditions, but we have found through more or less bitter experience sometimes that our construction projects vary much more widely than do different laboratories in their practices, and not always do our best cements, as we believe them to be from laboratory tests, give us the best results in the field. There is no good reason why field control methods should not approximate very closely our laboratory methods, but until they do we are certainly not justified in discriminating very closely between materials.

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[1] Professor of Applied Mechanics, Kansas State Agricultural College, and Consulting Materials Engineer, Kansas Highway Commission, Manhattan, Kans.

MR. D. A. ABRAMS.[1]—There are a number of questions that occur to me that have not been answered in the discussion. Why did the authors depart from the standard method of testing concrete cylinders? 6 by 12-in. cylinders have been used so widely that it seemed that they would have adhered to that practice.

I do not understand the purpose of using the drier mixtures. The curves were mostly on the dry side, rather than on the plastic side; many batches showed no slump whatever.

Investigations by other laboratories, where sufficient tests were made to iron out accidental variations, have shown a close sympathy between flexure and compression. I believe that if the authors of this paper had made enough tests they would have found a much closer agreement.

MR. SCHOLER.—In answer to the question as to specimens, we did not have the material available to make up the compression tests. We did not get sufficient quantities of it in time. We did not expect to go so far with the investigation at the time we started out, and as we had the beam ends available made the compression test upon them. The Iowa Highway Department last year was using that regularly in field control work, and we followed the same method in this investigation.

When the erratic results were secured time did not permit duplicating the results with compression cylinders and the values are given merely as information.

A MEMBER.—It seems to me it is rather doubtful practice to make compression tests on a beam after it has been broken in flexure. That might account for the erratic comparison between flexural strength and compressive strength.

MR. KOENITZER.—That same question occurred to us as to whether the breaking of the specimen in flexure and testing it in compression the same day did not have some effect upon it, and perhaps the best way to get away from that would be to test the pecimen in compression at a later date.

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[1] Director of Research, International Cement Corp., New York City.

THE RELATION BETWEEN THE STRENGTHS OF CEMENTS DEVELOPED BY MORTAR SPECIMENS AND CONCRETE SPECIMENS[1]

BY J. R. DWYER[2] AND P. H. BATES[3]

SYNOPSIS

Improvement in the standard acceptance strength tests for cements is very desirable. With the intention of promoting discussion and study of this subject there are herein presented data showing relations between strengths developed by a number of portland cements in various concretes and small mortar specimens when tested over a considerable range in time.

The trend of curves showing relations at several ages between the three types of mortar specimens and the several concretes are rather similar, but the values of the ratios showing these relations are in many cases far from identical.

All cements in one kind of mortar specimens develop a strength which has a certain relation to the strength of the same cement in a certain concrete, but the ratio changes with age of testing and the change in kind, grading and amount of aggregate.

Much study has been given to various methods for determining the strength properties of portland cements. The present standard strength test has been criticized and various modifications thereof or substitutes therefor have been studied. Some of the data have been of assistance in planning further work, but to date none of the proposed methods through any demonstrated merit has supplanted the present mortar tension test. Nevertheless, improvement in the standard acceptance strength test is certainly to be desired if it is assumed that the principal requisite for a satisfactory acceptance strength test for cement is that the test will be reasonably indicative of the strength behaviors of different cements when used in concretes —at least in concretes of about average properties.

With the intention of promoting discussion and study of this subject, there are herein presented certain data, obtained in the course of another investigation, showing the relations between the strengths developed by several portland cements in various concretes and small mortar specimens. It is not considered that these data are sufficiently complete to form the basis for any very definite conclusions, but they should be of interest as furnishing comparisons of mortar-concrete strength relations for various combinations of different cements and aggregates when tested over a considerable range in time.

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[1] Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce, Washington, D. C.

[2] Research Associate, U. S. Bureau of Standards, Washington, D. C.

[3] Chief, Clay and Silicate Products Division., U. S. Bureau of Standards, Washington, D. C.

MATERIALS

The four portland cements, designated cements A, B, C and D, display a considerable range in their strengths, particularly at the earlier ages, as is well shown by the standard mortar tensile strengths in Table V, although none of the cements were of unusually high strength. They were selected as displaying different but not unusual strength properties. The results of the usual physical tests and chemical analyses are shown in Tables I and II, respectively.

TABLE I.—PHYSICAL PROPERTIES OF CEMENTS.

	Fineness, per cent retained on No. 200 Sieve	Soundness in Steam	Setting Time, Gillmore				Tensile Strength, 1:3 Standard Sand Mortar, lb. per sq. in.		Normal Consistency, Water per cent by weight
			Initial Set		Final Set				
			hours	minutes	hours	minutes	7 days	28 days	
Cement A	21.3	OK	4	00	6	00	340	400	22.0
Cement B	20.5	OK	5	30	7	15	225	355	21.4
Cement C	21.0	OK	3	45	6	15	210	330	21.0
Cement D	20.8	OK	5	15	7	00	325	385	21.5

TABLE II.—CHEMICAL ANALYSES OF CEMENTS.

	SiO_2, per cent	Fe_2O_3, per cent	Al_2O_3, per cent	CaO, per cent	MgO, per cent	SO_3, per cent	Loss on Ignition, per cent	Insoluble Matter, per cent
Cement A	20.9	2.8	6.0	63.9	3.3	1.6	0.9	0.3
Cement B	23.1	2.4	5.3	62.3	3.2	1.6	1.1	0.1
Cement C	22.3	2.0	5.3	62.7	4.0	1.7	1.6	0.2
Cement D	22.9	2.1	5.5	63.0	3.3	1.6	1.0	0.2

TABLE III.—MECHANICAL ANALYSES OF AGGREGATES.

	Coarse Aggregate					Potomac Sand
	Grading B	Grading F	Grading I	Grading K	Grading L	
Retained on 1½-in. Sieve, per cent	0	0	0	0	0	..
Retained on ¾-in. Sieve, per cent	0	33	17	50	100	..
Retained on ⅜-in. Sieve, per cent	50	83	50	100	...	..
Retained on No. 4 Sieve, per cent	100	100	100	...	...	4
Retained on No. 8 Sieve, per cent	...	...	...	...	...	19
Retained on No. 16 Sieve, per cent	...	...	...	...	...	31
Retained on No. 30 Sieve, per cent	...	...	...	...	...	50
Retained on No. 50 Sieve, per cent	...	...	...	...	...	86
Retained on No. 100 Sieve, per cent	...	...	...	...	...	97

The "standard" sand was the Ottawa sand regularly used in cement testing. Potomac River sand was used as the fine aggregate for all concretes and also for the mortar specimens where indicated. The mechanical analysis of the Potomac River sand is given in Table III.

TABLE IV.—MIXING WATER FOR CONCRETES AND MORTARS.

	Cement A	Cement B			Cement C	Cement D
	Gravel	Gravel	Limestone	Slag	Gravel	Gravel
CONCRETE: RATIO OF WATER TO CEMENT, BY VOLUME						
GRADING B:						
Mix 1:1½:3	....	0.86	0.92	1.00	....	....
Mix 1:2:4	1.09	1.09	1.19	1.27	1.07	1.08
Mix 1:3:6	....	1.60	1.70	1.84	....	....
GRADING F:						
Mix 1:1½:3	....	0.82	0.87	0.90	....	....
Mix 1:2:4	1.04	1.03	1.10	1.14	1.01	1.02
Mix 1:3:6	....	1.51	1.57	1.73	....	....
GRADING I:						
Mix 1:1½:3	....	0.85	0.92	0.97	....	....
Mix 1:2:4	1.10	1.09	1.16	1.22	1.08	1.08
Mix 1:3:6	....	1.59	1.71	1.81	....	....
GRADING K:						
Mix 1:1½:4½	0.97	....	....	....	0.94	0.94
Mix 1:2:4	1.02	....	....	....	1.00	1.00
Mix 1:3:3	1.22	....	....	....	1.22	1.21
Mix 1:4½:1½	1.64	....	....	....	1.63	1.61
GRADING L:						
Mix 1:1½:4½	0.89	....	....	....	0.86	0.87
Mix 1:2:4	0.96	....	....	....	0.93	0.95
Mix 1:3:3	1.19	....	....	....	1.17	1.17
Mix 1:4½:1½	1.60	....	....	....	1.61	1.60
MORTAR: WATER EXPRESSED AS PERCENTAGE OF DRY MATERIALS, BY WEIGHT						
Standard Sand, 1:3	10.2	10.1			10.1	10.2
Potomac Sand, 1:3	13.7	13.6			13.6	13.7

The coarse aggregates were Potomac River gravel, limestone and blast-furnace slag. Not all aggregates were used for each gradation and proportion, or with each cement. The mechanical analyses of the various gradings of coarse aggregates are shown in Table III. On the one hand, the gradings B, F and I were selected from among ten gradings as being somewhat different in their composition, yet of about average values as indicated by the workability and strength of the concretes in which they were used. On the other hand, gradings K and L were selected since they were deficient in some of the smaller sizes and were of such nature that the concrete made with them was improved, both with respect to workability and strength, by oversanding beyond the frequently used 1:2 ratio of fine to coarse aggregates.

PREPARATION OF SPECIMENS

The standard sand mortars were prepared in accordance with the standard specifications for testing portland cement.[1] The Potomac River sand mortars were made in the same general manner, but using such quantity of mixing water as would, in the judgment of an experienced operator, produce in these mortars a consistency similar to that of the standard sand mortars. The water contents are shown in Table IV.

The briquets were prepared in accordance with the specifications mentioned above, while the 2-in. cubes were molded in a closely similar manner. The 2 by 4-in. cylinders were molded in the manner prescribed by the society.[2] All mortar specimens, after 24 hours in moist air, were stored in water until time of test.

The concretes were mixed by hand, each batch being of a size sufficient to make one 6 by 12-in. cylinder. Sufficient water was added to produce concrete with a flow of 95 as measured on the flow table, using fifteen $\frac{1}{8}$-in. drops and expressing the flow as the percentage of increase in the original diameter. It is not claimed that equality of flow thus measured is indicative of equal workability throughout the range of proportions, gradations and materials used; but the flow table was selected as apparently the best device then available for adjusting the water content so as to produce concretes of nearly similar working qualities. After 24 hours in the molds, the concrete specimens were stored in moist air until the time of test.

The schedule of making the concrete specimens containing cements A, C and D was arranged so as to eliminate in so far as possible effects of variations in conditions. The gravel concrete specimens containing cement B were made up considerably earlier than the specimens containing the other cements, but an examination of the

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[1] A.S.T.M. Standard Specifications and Tests for Portland Cement (C 9 - 26), 1927 Book of A.S.T.M. Standards, Part II, p. 23.

[2] A.S.T.M. Tentative Specifications and Tests for Compressive Strength of Portland-Cement Mortars (C 9 - 16 T), *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part I, p. 599 (1920); also 1929 Book of A.S.T.M. Tentative Standards, p. 196.

TABLE V.—COMPARISON OF STRENGTHS OF FOUR CEMENTS IN MORTARS AND CONCRETES.

Flow of Concrete Approximately 95 per cent.
See Table IV for water-cement relations.
Potomac gravel used as coarse aggregate in concretes.

Mix	Kind of Test and Specimen	Cement	Strength of Mortar, lb. per sq. in.						Grading B						Grading F						Grading I					
			1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
									COMPRESSIVE STRENGTH OF CONCRETE, LB. PER SQ. IN.																	
Concrete, 1:2:4 by volume	Compression, 6 by 12-in. cylinders........	A	...	...	...	...	...	...	170	660	1330	2690	3180	3480	195	720	1360	2600	3070	3220	185	250	1380	2610	3000	3170
		B	...	...	...	...	...	...	95	300	630	1690	2940	3320	100	340	700	1820	2980	3420	95	310	600	1760	2820	3360
		C	...	...	...	...	...	...	135	480	850	2160	2980	3030	180	520	980	2190	3100	3290	155	460	860	1890	2830	3350
		D	...	...	...	...	...	...	135	440	910	2280	3200	3670	155	570	1040	2420	3270	3690	140	500	980	2270	3190	3700
									MORTAR STRENGTHS EXPRESSED AS PERCENTAGES OF CORRESPONDING CONCRETE STRENGTHS																	
Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. Standard briquets	A	110	240	340	400	385	350	65	36	26	15	12	10	56	33	25	15	13	11	59	32	25	15	13	11
		B	75	170	225	355	400	375	79	57	36	21	14	11	75	50	32	20	13	11	79	55	38	20	14	11
		C	55	180	210	330	345	300	41	38	25	15	12	10	31	35	21	15	11	9	36	39	24	17	12	9
		D	80	200	325	385	405	395	59	45	36	17	13	11	52	35	31	16	12	11	57	40	33	17	13	11
Mortar, 1:3 by weight Standard Sand	Compression, 2-in. cubes	A	680	1880	3430	4820	5560	5150	400	285	258	179	175	148	349	261	252	185	181	160	368	251	249	185	185	162
		B	415	1030	1620	3500	4990	5200	437	343	257	207	170	157	415	303	231	192	167	152	437	332	270	199	177	155
		C	405	1220	1950	3300	4640	4360	300	254	229	153	156	144	225	235	199	151	150	133	261	265	227	175	164	130
		D	510	1410	2410	4370	6060	5660	378	321	265	192	189	154	329	247	232	181	185	153	364	282	246	193	190	153
Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	A	615	1550	2520	4340	4890	5100	362	235	189	162	154	147	315	215	185	167	159	158	332	207	183	166	163	161
		B	360	940	1530	3160	3900	4000	379	313	243	187	133	120	360	276	219	174	131	117	379	303	255	180	138	119
		C	515	1040	1430	2490	3620	3110	381	217	168	115	121	103	286	200	146	114	117	95	332	226	166	132	128	93
		D	510	1170	2060	3860	5170	4280	378	266	227	169	162	117	329	205	198	160	158	116	364	234	210	170	162	116
Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. Standard briquets	A	75	265	395	490	500	520	44	40	30	18	16	15	38	37	29	19	16	16	41	35	29	19	17	16
		B	65	175	255	405	495	510	68	58	40	24	17	15	65	51	36	22	17	15	68	56	43	23	18	15
		C	70	180	270	385	400	485	52	38	32	18	13	16	39	35	28	18	13	15	45	39	32	20	14	14
		D	70	200	325	435	485	505	52	45	36	19	15	14	45	35	31	18	15	14	50	40	33	19	15	14
Mortar, 1:3 by weight, Potomac Sand	Compression, 2-in. cubes	A	560	1930	3590	5710	6340	6250	329	292	270	212	199	180	287	268	264	219	207	194	303	257	260	219	211	197
		B	390	1020	1900	4170	6110	6370	411	340	302	247	208	192	390	300	271	229	205	186	411	329	317	237	217	190
		C	415	1220	2180	4340	5700	6400	307	254	257	201	191	211	231	235	223	198	184	195	268	265	254	230	201	191
		D	465	1340	2540	4740	6310	6500	344	305	279	208	197	177	300	235	244	196	193	176	332	268	259	209	198	176
Mortar, 1:3 by weight, Potomac Sand	Compression, 2 by 4-in. cylinders	A	455	1590	2880	4690	5740	6000	268	241	217	174	181	172	233	221	212	181	187	186	246	212	209	180	191	189
		B	280	820	1500	3680	5320	5720	295	273	238	218	181	172	280	241	214	202	179	167	295	265	250	209	189	170
		C	335	1100	1960	3460	4730	5590	248	229	231	160	159	185	186	212	200	158	153	170	216	239	228	183	167	167
		D	410	1090	1900	3790	5800	5730	304	248	209	166	181	156	265	191	183	157	177	155	293	218	194	167	182	155

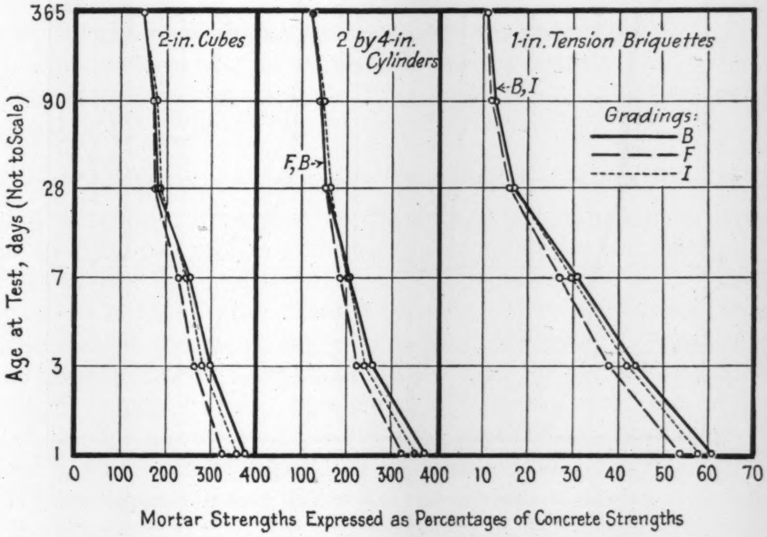

FIG. 1.—Strength Relations of 1:3 Standard Sand Mortars and 1:2:4 Gravel Concretes, Using Three Gradings of Coarse Aggregate and Averaging the Relations of Cements A, B, C and D.

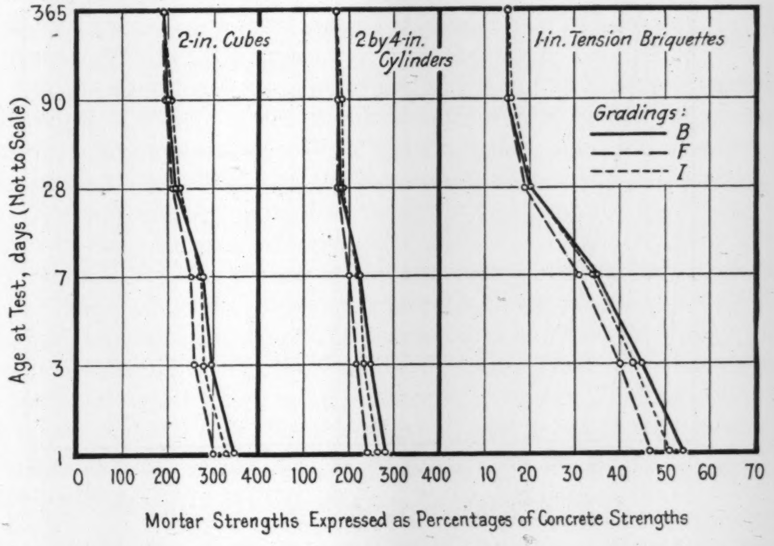

FIG. 2.—Strength Relations of 1:3 Potomac Sand Mortars and 1:2:4 Gravel Concretes, Using Three Gradings of Coarse Aggregate and Averaging the Relations of Cements A, B, C and D.

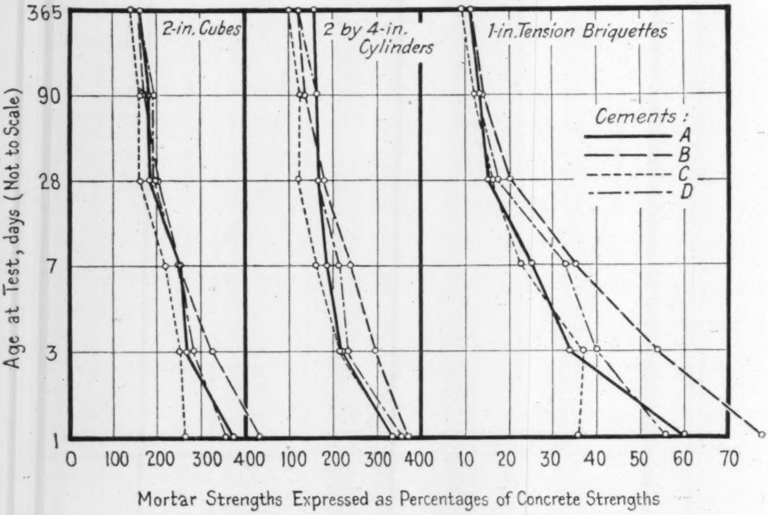

FIG. 3.—Strength Relations of 1:3 Standard Sand Mortars and 1:2:4 Gravel Concrete, Using Average of Relations for Gradings B, F and I of Aggregates and Separately Plotting Relations for each of four Cements.

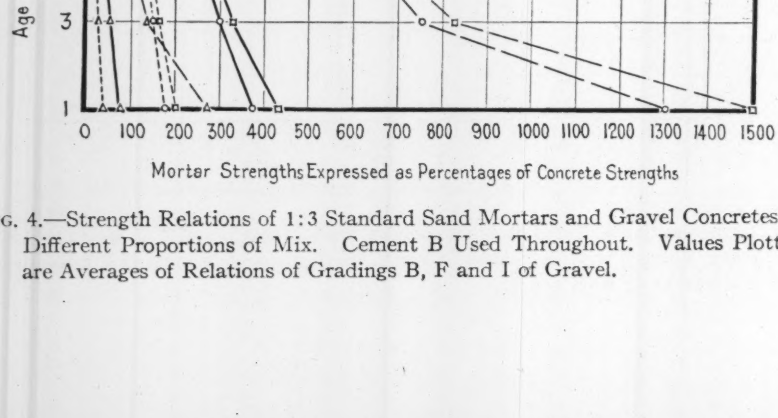

FIG. 4.—Strength Relations of 1:3 Standard Sand Mortars and Gravel Concretes of Different Proportions of Mix. Cement B Used Throughout. Values Plotted are Averages of Relations of Gradings B, F and I of Gravel.

mortar strengths, as well as other data, confirms the relatively low strength values produced by cement B at the early ages.

The tensile strengths are recorded to the nearest 5 lb., while the compressive strengths are generally given to the nearest 10 lb. Each strength value is the average of three test results.

DATA AND DISCUSSION

A very brief inspection of the data in the tables demonstrates that the ratios of mortar strength to concrete strength, for any particular mortar test and a given concrete, change with age. Also, at any age, a change in the strength of the concrete will effect a change in the ratio of mortar strength to concrete strength. Therefore, the data herein presented seem of interest because they afford comparisons between the results of a number of different mortar tests and the effects on the mortar-concrete strength relations resulting from variations in the cements, aggregates and combinations thereof.

In some parts of this discussion use is made of the average values of the mortar-concrete strength ratios for three or four cements for a given combination of variables. It is assumed that such averages are sufficiently indicative of cements not widely different from those used in these tests to serve as matter for discussion herein. However, it should be understood that differences in the strength performances of individual cements must not be minimized or ignored in processes of averaging data for a number of cements.

At the outset, attention is invited to the not unusual retrogression in strengths of some of the standard sand mortar specimens, in both tension and compression. With one exception, such retrogression in strength is not exhibited by the Potomac River sand mortars.

When studying the relative merits of small mortar specimens for use in testing the concrete-making qualities of cements, there arises a question as to the nature of the concrete which should be chosen as the basis of study. Gravel concrete of the nominal 1:2:4 proportions, and of easily workable consistency, has been so widely used that it is selected for the basis of the first examination of the relation of the mortar strengths to the concrete strengths. These relations are given in detail in Table V and are illustrated in Figs. 1, 2 and 3.

In Fig. 1 are plotted the average values of the ratios for the four cements for each of the gradings B, F and I, the data being taken from Table V. The general arrangement of the curves for each of the three specimens is quite similar, the trend being the same throughout, with the differences between gradings most marked at the early ages, and diminishing with age until at the end of one year the ratios are about

TABLE VI.—COMPARISON OF STRENGTHS OF MORTARS AND 1:1.5:3 CONCRETES, USING CEMENT B THROUGHOUT.

Flow of Concrete Approximately 95 per cent.
See Table IV for water-cement relations.

Mix	Kind of Test and Specimen	Concrete Coarse Aggregate	Strength of Mortar, lb. per sq. in.						Grading B						Grading F						Grading I					
			1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
									COMPRESSIVE STRENGTH OF CONCRETE, LB. PER SQ. IN.																	
Concrete, 1:1.5:3 by volume	Compression, 6 by 12-in. cylinders	Gravel	...	...	...	...	...	...	185	630	1190	2950	4790	5250	225	640	1250	3130	4500	4910	205	640	1210	3020	4330	5110
		Limestone	...	...	...	...	...	...	140	520	1080	2610	3640	4210	205	590	1180	2660	3680	4010	185	600	1040	2580	3840	4580
		Slag	...	...	...	...	...	...	140	480	880	2080	3840	4450	205	590	1160	3160	4720	5150	155	540	880	2470	4000	4680
									MORTAR STRENGTHS EXPRESSED AS PERCENTAGES OF CORRESPONDING CONCRETE STRENGTHS																	
Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. briquets	Gravel	75	170	225	355	400	375	41	27	19	12	8	7	33	827	18	11	9	8	37	27	19	12	9	7
		Limestone	...	...	...	...	...	...	54	33	21	14	11	9	37	29	19	13	11	9	41	28	22	14	10	8
		Slag	...	...	...	...	...	...	54	35	26	17	10	8	37	29	19	11	8	7	48	31	26	14	10	8
Mortar, 1:3 by weight, Standard Sand	Compression, 2-in. cubes	Gravel	415	1030	1620	3500	4990	5200	224	163	136	119	•104	99	184	161	130	112	111	106	202	161	134	116	115	102
		Limestone	...	...	...	...	...	...	296	198	150	134	137	124	202	175	137	132	136	130	224	172	156	136	130	113
		Slag	...	...	...	...	...	...	296	215	184	168	130	117	202	175	140	111	106	101	268	191	184	142	125	111
Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	Gravel	360	940	1530	3160	3900	4000	195	149	129	107	81	76	160	147	122	101	87	81	176	147	126	105	90	78
		Limestone	...	...	...	...	...	...	257	181	142	121	107	95	176	159	130	119	106	100	195	157	147	122	102	87
		Slag	...	...	...	...	...	...	257	196	174	152	102	90	176	159	132	100	83	78	232	174	174	128	98	85
Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. briquets	Gravel	65	175	255	405	495	510	35	28	21	14	10	10	29	27	20	13	11	10	32	27	21	13	11	10
		Limestone	...	...	...	...	...	...	46	34	24	16	14	12	32	30	22	15	13	13	35	29	25	16	13	11
		Slag	...	...	...	...	...	...	46	36	29	19	13	11	32	30	22	13	10	10	42	32	29	16	12	11
Mortar, 1:3 by weight, Potomac Sand	Compression, 2-in. cubes	Gravel	390	1020	1900	4170	6110	6370	211	162	160	141	128	121	173	159	152	133	136	130	190	159	157	138	141	125
		Limestone	...	...	...	...	...	...	279	196	176	160	168	151	190	173	161	157	166	159	211	170	183	162	159	139
		Slag	...	...	...	...	...	...	279	212	216	200	159	143	190	173	164	132	129	124	252	189	216	169	153	136
Mortar, 1:3 by weight, Potomac Sand	Compression, 2 by 4-in. cylinders	Gravel	280	820	1500	3680	5320	5720	151	130	126	125	111	109	124	128	120	117	118	117	137	128	124	122	123	112
		Limestone	...	...	...	...	...	...	200	158	139	141	146	136	137	139	127	138	145	143	151	137	144	143	139	125
		Slag	...	...	...	...	...	...	200	171	170	177	139	129	137	139	129	116	113	111	181	152	170	149	133	122

TABLE VII.—COMPARISON OF STRENGTHS OF MORTARS AND 1:2:4 CONCRETES, USING CEMENT B THROUGHOUT.

Flow of Concrete Approximately 95 per cent.

See Table IV for water-cement relations.

Mix	Kind of Test and Specimen	Concrete Coarse Aggregate	Strength of Mortar, lb. per sq. in.						Grading B						Grading F						Grading I					
			1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
									COMPRESSIVE STRENGTH OF CONCRETE, LB. PER SQ. IN.																	
Concrete, 1:2:4 by volume	Compression, 6 by 12-in. cylinders	Gravel	...	...	...	...	...	...	95	300	630	1690	2940	3320	100	340	700	1820	2980	3420	95	310	600	1760	2820	3360
		Limestone	...	...	...	...	...	...	75	270	560	1410	2360	2890	110	360	750	1710	2680	2970	80	300	580	1530	2360	2970
		Slag	...	...	...	...	...	...	70	280	460	1240	2290	2760	120	380	700	1640	2940	3330	95	300	530	1380	2620	3220
									MORTAR STRENGTHS EXPRESSED AS PERCENTAGES OF CORRESPONDING CONCRETE STRENGTHS																	
Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. briquets	Gravel	75	170	225	355	400	375	79	57	36	21	14	11	75	50	32	20	13	11	79	55	38	20	14	11
		Limestone	...	...	...	...	...	...	100	63	40	25	17	13	68	47	30	21	15	13	94	57	39	23	17	13
		Slag	...	...	...	...	...	...	107	61	49	29	17	14	62	45	32	22	14	11	79	57	42	26	15	12
Mortar, 1:3 by weight, Standard Sand	Compression, 2-in. cubes	Gravel	415	1030	1620	3500	4990	5200	437	343	257	207	170	157	415	303	231	192	167	152	437	332	270	199	177	155
		Limestone	...	...	...	...	...	...	553	382	289	248	211	180	377	286	216	204	186	175	519	343	279	229	211	175
		Slag	...	...	...	...	...	...	593	368	352	282	218	188	346	271	231	213	170	156	437	343	306	254	190	161
Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	Gravel	360	940	1530	3160	3900	4000	379	313	243	187	133	120	360	276	219	174	131	117	379	303	255	180	138	119
		Limestone	...	...	...	...	...	...	480	348	273	224	165	138	327	261	204	185	146	135	450	313	264	207	165	135
		Slag	...	...	...	...	...	...	514	336	333	255	170	145	300	247	219	193	133	120	379	313	289	229	149	124
Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. briquets	Gravel	65	175	255	405	495	510	68	58	40	24	17	15	65	51	36	22	17	15	68	56	42	23	18	15
		Limestone	...	...	...	...	...	...	87	65	46	29	21	18	59	49	34	24	18	17	81	58	44	26	21	17
		Slag	...	...	...	...	...	...	93	62	55	33	22	18	54	46	36	25	17	15	68	58	48	29	19	15
Mortar, 1:3 by weight Potomac Sand	Compression, 2-in. cubes	Gravel	390	1020	1900	4170	6110	6370	411	340	302	247	208	192	390	300	271	229	205	186	411	329	317	237	217	190
		Limestone	...	...	...	...	...	...	520	378	339	296	259	220	354	283	253	244	228	214	488	340	328	272	259	214
		Slag	...	...	...	...	...	...	557	364	413	336	267	231	325	268	271	254	208	191	411	340	359	302	233	198
Mortar, 1:3 by weight, Potomac Sand	Compression, 2 by 4-in. cylinders	Gravel	280	820	1500	3680	5320	5720	295	273	238	218	181	172	280	241	214	202	178	167	295	265	250	209	189	170
		Limestone	...	...	...	...	...	...	373	304	268	261	226	198	254	228	200	215	199	193	350	273	259	241	225	193
		Slag	...	...	...	...	...	...	400	293	326	297	232	207	233	216	214	224	181	172	295	273	283	267	203	178

TABLE VIII.—COMPARISON OF STRENGTHS OF MORTARS AND 1:3:6 CONCRETES, USING CEMENT B THROUGHOUT.

Flow of Concrete Approximately 95 per cent.
See Table IV for water-cement relations.

Mix	Kind of Test and Specimen	Concrete Coarse Aggregate	Strength of Mortar, lb. per sq. in.						Grading B						Grading F						Grading I					
			1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
									COMPRESSIVE STRENGTH OF CONCRETE, LB. PER SQ. IN.																	
Concrete, 1:3:6 by volume	Compression, 6 by 12-in. cylinders	Gravel	...	...	...	...	...	...	25	110	240	690	1350	1670	35	150	290	820	1420	1710	25	120	260	680	1420	1730
		Limestone	...	...	...	...	...	...	30	140	270	640	1110	1440	60	180	360	810	1400	1820	45	160	280	680	1080	1380
		Slag	...	...	...	...	...	...	35	140	250	620	1090	1320	60	210	320	730	1370	1630	50	160	280	610	1060	1430
									MORTAR STRENGTHS EXPRESSED AS PERCENTAGES OF CORRESPONDING CONCRETE STRENGTHS																	
Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. briquets	Gravel	75	170	225	355	400	375	300	154	94	51	30	22	214	113	78	43	28	22	300	142	87	52	28	22
		Limestone	...	...	...	...	...	...	250	121	83	55	36	26	125	94	63	44	29	21	167	106	80	52	37	27
		Slag	...	...	...	...	...	...	214	121	90	57	37	28	125	81	70	49	29	23	150	106	80	58	38	26
Mortar, 1:3 by weight, Standard Sand	Compression, 2-in. cubes	Gravel	415	1030	1620	3500	4990	5200	1660	936	675	507	370	311	1186	687	559	427	351	304	1660	858	623	515	351	301
		Limestone	...	...	...	...	...	...	1383	736	600	547	450	361	692	572	450	432	356	286	922	644	579	515	462	377
		Slag	...	...	...	...	...	...	1186	736	648	565	458	394	692	490	506	479	364	319	830	644	579	574	471	364
Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	Gravel	360	940	1530	3160	3900	4000	1440	855	638	458	289	240	1029	627	528	385	275	234	1440	783	588	465	275	231
		Limestone	...	...	...	...	...	...	1200	671	567	494	351	278	600	522	425	390	279	220	800	588	546	465	361	290
		Slag	...	...	...	...	...	...	1029	671	612	510	358	303	600	448	478	433	285	245	720	588	546	518	368	280
Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. briquets	Gravel	65	175	255	405	495	510	260	159	106	59	37	31	186	117	88	49	35	30	260	146	98	60	35	29
		Limestone	...	...	...	...	...	...	217	125	94	63	45	35	108	97	71	50	35	28	144	109	91	60	46	37
		Slag	...	...	...	...	...	...	186	125	102	65	45	39	108	83	80	55	36	31	130	109	91	66	47	36
Mortar, 1:3 by weight, Potomac Sand	Compression, 2-in. cubes	Gravel	390	1020	1900	4170	6110	6370	1560	927	792	604	453	381	1115	680	655	509	430	373	1560	850	731	613	430	368
		Limestone	...	...	...	...	...	...	1300	729	704	652	550	442	650	567	528	515	436	350	867	638	679	613	566	462
		Slag	...	...	...	...	...	...	1114	729	760	673	561	483	650	486	594	571	446	391	780	638	679	684	576	445
Mortar, 1:3 by weight, Potomac Sand	Compression, 2 by 4-in. cylinders	Gravel	280	820	1500	3680	5320	5720	1120	745	625	533	394	343	800	547	517	449	375	335	1120	683	577	541	375	331
		Limestone	...	...	...	...	...	...	930	586	556	575	479	397	467	456	417	454	380	314	622	512	536	541	493	414
		Slag	...	...	...	...	...	...	800	586	600	594	488	433	467	390	469	504	388	351	560	512	536	603	502	400

the same for the three gradings with respect to any particular mortar test. Similar data are plotted in Fig. 2, using only the relations derived for the Potomac River sand mortars. In both Figs. 1 and 2, the relations for gradings B, F and I generally appear in the same order of position for any given mortar specimen. Because of the general lack of retrogression in the Potomac sand mortars, the lines joining the relations at the 3-months and 1-year tests are more nearly vertical than for the standard sand mortars.

In the 1-day tests the ratios of the cubes were closely alike for both standard and Potomac sands, while the ratios were slightly higher for the cylinders and briquets when using the standard sand. At 3 days there was but little difference in the ratios for the two sands for any of the mortar specimens. At 7 days and longer periods the Potomac River sand mortars gave slightly higher ratios than did the standard sand mortars.

Since the comparison of Figs. 1 and 2 indicates no great difference in the general trend of ratios of the two sands, or their agreement within themselves, the values of the Potomac sand mortars are not plotted in subsequent figures, although they are given in the tables.

In Fig. 3 are plotted the average values of the mortar-concrete strength ratios for gradings B, F and I, plotting each of the cements separately. In general, at the earlier ages, the curves of the individual cements are in the same order of arrangement for the three different mortar tests. However, it should be noted in Table V that much greater differences in strength relations are produced by changing the cements than by changing the gradings of the coarse aggregates. This is particularly noticeable at the 3 and 7-day ages.

Attention is invited particularly to the 7-day age—one of the present standard test ages—at which time cements C and D show decidedly different ratios for the standard tension test, although producing concretes of about the same strengths. Cement B produced concretes and mortars considerably different in strength properties at early ages from those made with cement D, but in Fig. 3 the ratios for these two cements are closely alike at 7 days. Cements A and C are not so different at ages later than 1 day, as indicated by the ratio of tensile mortar strength to concrete strength, and still their strengths in concretes and mortars varied widely. In general, it appears that at the 1-day age the 2 by 4-in. cylinders gave ratios more nearly alike than did the cubes, although at the later ages the variations in ratios of the cubes become less.

Table IX.—Comparison of Strengths of Three Cements in Mortars and Concretes.

Flow of Concrete approximatly 95 per cent.
See Table IV for water-cement relations.
Concrete aggregates: Potomac sand and gravel.
Gradings K and L deficient in smaller sizes of coarse aggregate, see Table III.

Grading of Coarse Aggregate	Mix	Kind of Test and Specimen	Cement	Strength of Mortar, lb. per sq. in.						Concrete Mix, 1:1.5:4.5, by Volume						Concrete Mix, 1:2:4, by Volume						Concrete Mix, 1:3:3, by Volume						Concrete Mix, 1:4.5:1.5, by Volume					
				1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
										Compressive Strength of Concrete, lb. per sq. in.																							
K	Concrete	Compression 6 by 12-in. cylinders	A	...	...	...	...	...	...	190	660	1100	1890	2370	2510	195	755	1220	2480	2860	3000	145	565	1100	2280	2350	2730	70	285	600	1210	1480	1270
			C	...	...	...	...	...	...	150	420	735	1570	2090	2540	180	570	900	1940	2680	3170	110	405	770	1740	2460	2730	50	205	410	930	1450	1740
			D	...	...	...	...	...	...	160	475	855	1840	2570	2830	160	535	990	2220	2900	3600	115	415	800	2020	2580	3010	60	170	385	1120	1420	1710
										Mortar Strengths Expressed as Percentages of Corresponding Concrete Strengths																							
	Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. briquets	A	110	240	340	400	385	350	58	36	31	21	16	14	56	31	28	16	13	12	76	42	31	18	16	13	157	84	57	33	26	28
			C	55	180	210	330	345	300	37	43	29	21	17	12	31	32	23	17	13	9	50	44	27	19	14	11	110	88	51	35	24	17
			D	80	200	325	385	405	395	50	42	38	21	16	14	50	37	33	17	14	11	70	48	41	19	16	13	133	118	84	34	29	23
	Mortar, 1:3 by weight, Standard Sand	Compression, 2-in. cubes	A	680	1880	3430	4820	5560	5150	358	284	312	255	235	205	349	249	281	194	194	172	469	332	312	211	237	189	971	660	572	398	376	406
			C	405	1220	1950	3300	4640	4360	270	290	265	210	222	172	225	214	217	170	173	138	368	301	253	190	189	160	810	595	475	355	320	251
			D	510	1410	2410	4370	6060	5660	319	297	282	238	236	200	319	264	243	197	209	157	443	340	301	216	235	188	850	829	626	390	427	331
	Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	A	615	1550	2520	4340	4890	5100	324	235	229	230	206	203	315	205	207	175	171	170	424	275	229	190	208	187	879	543	420	359	330	402
			C	515	1040	1430	2490	3620	3110	343	248	195	159	173	122	286	182	159	128	135	98	468	257	186	143	147	114	1030	507	349	268	250	179
			D	510	1170	2060	3860	5170	4280	319	246	241	209	201	151	319	219	208	174	178	119	443	282	258	191	200	142	850	688	535	345	364	250
	Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. briquets	A	75	265	395	490	500	520	39	40	36	26	21	21	38	35	32	20	17	17	52	47	36	21	21	19	107	93	66	40	34	41
			C	70	180	270	385	400	485	47	43	37	24	19	19	39	32	30	20	15	15	64	44	35	22	16	18	140	88	66	41	28	28
			D	70	200	325	435	485	505	44	42	38	24	19	18	44	37	33	20	17	14	61	48	41	22	19	17	117	118	84	39	34	30
	Mortar, 1:3 by weight, Potomac Sand	**Compression, 2-in. cubes**	A	560	1930	3590	5710	6340	6250	294	292	326	302	268	249	287	256	294	230	222	208	386	342	326	250	270	229	800	677	598	472	428	492
			C	415	1220	2180	4340	5700	6400	277	290	297	276	273	252	230	214	242	224	213	202	377	301	283	249	232	234	830	595	532	467	393	368
			D	465	1340	2540	4740	6310	6500	291	282	297	258	246	230	291	250	257	214	218	181	404	323	318	235	245	216	775	788	660	423	444	380
	Mortar, 1:3 by weight, Potomac Sand	**Compression, 2 by 4-in. cylinders**	A	455	1590	2880	4690	5740	6000	239	241	262	248	242	239	233	211	236	189	201	200	314	281	262	206	244	220	650	558	480	388	388	472
			C	335	1100	1960	3460	4730	5590	223	262	267	220	226	220	186	193	218	178	176	176	305	272	255	199	192	205	670	537	478	372	326	321
			D	410	1090	1900	3790	5800	5730	256	229	223	206	226	202	256	204	192	171	200	159	357	263	238	188	225	190	683	641	494	338	408	335

TABLE IX.—*Continued.*

Grading of Coarse Aggregate	Mix	Kind of Test and Specimen	Cement	Strength of Mortar, lb. per sq. in.						Concrete Mix, 1:1.5:4.5, by Volume						Concrete Mix, 1:2:4, by Volume						Concrete Mix, 1:3:3, by Volume						Concrete Mix, 1:4 5:1:5, by Volume					
				1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year	1 day	3 days	7 days	28 days	3 mo.	1 year
										COMPRESSIVE STRENGTH OF CONCRETE, LB. PER SQ. IN.																							
L	Concrete	Compression, 6 by 12-in. cylinders	A	...	...	...	...	...	...	210	615	1100	1890	2090	2360	180	700	1220	2220	2550	2700	125	640	1060	2250	2600	2730	65	355	720	1310	1500	1480
			C	...	...	...	...	...	...	160	530	890	2020	2500	2680	145	510	965	2020	2580	2700	110	455	805	1810	2460	3040	55	200	400	890	1520	1720
			D	...	...	...	...	...	...	150	490	900	1790	2410	2540	135	490	860	1880	2590	3000	105	390	860	1980	2870	3240	50	190	435	1090	1720	1940
										MORTAR STRENGTHS EXPRESSED AS PERCENTAGES OF CORRESPONDING CONCRETE STRENGTHS																							
	Mortar, 1:3 by weight, Standard Sand	Tension, 1-in. briquets	A	110	240	340	400	385	350	52	39	31	21	18	15	61	34	28	18	15	13	88	38	32	18	15	13	169	68	47	30	26	24
			C	55	180	210	330	345	300	34	34	24	16	14	11	38	35	22	16	13	11	50	40	26	18	14	10	100	90	53	37	23	17
			D	80	200	325	385	405	395	53	41	36	22	17	16	59	41	38	20	16	13	76	51	38	19	14	12	160	105	75	35	24	20
	Mortar, 1:3 by weight, Standard Sand	Compression, 2-in. cubes	A	680	1880	3430	4820	5560	5150	324	306	312	255	266	218	378	269	281	217	218	191	544	294	324	214	214	189	1046	530	476	368	371	348
			C	405	1220	1950	3300	4640	4360	253	230	219	163	186	162	279	239	202	163	180	161	368	268	242	182	189	143	736	610	488	371	305	253
			D	510	1410	2410	4370	6060	5660	340	288	268	244	251	223	378	288	280	232	234	189	486	362	280	221	211	175	1020	742	554	401	352	292
	Mortar, 1:3 by weight, Standard Sand	Compression, 2 by 4-in. cylinders	A	615	1550	2520	4340	4890	5100	293	252	229	230	234	216	342	221	207	195	192	189	492	242	238	193	188	187	946	437	350	331	326	345
			C	515	1040	1430	2490	3620	3110	322	196	161	123	145	116	355	204	148	123	140	115	468	229	178	138	147	102	936	520	358	280	238	181
			D	510	1170	2060	3860	5170	4280	340	239	229	216	215	169	378	239	240	205	200	143	486	300	240	195	180	132	1020	616	474	354	301	221
	Mortar, 1:3 by weight, Potomac Sand	Tension, 1-in. briquets	A	75	265	395	490	500	520	36	43	36	26	24	22	42	38	32	22	20	19	60	41	37	22	19	19	115	75	55	37	33	35
			C	70	180	270	385	400	485	44	34	30	19	16	18	48	35	28	19	16	18	64	40	34	21	16	16	127	90	68	43	26	28
			D	70	200	325	435	485	505	47	41	36	24	20	20	52	41	38	23	19	17	67	51	38	22	17	16	140	105	75	40	28	26
	Mortar, 1:3 by weight, Potomac Sand	Compression, 2-in. cubes	A	560	1930	3590	5710	6340	6250	267	314	326	302	303	265	311	276	294	257	249	231	448	302	339	254	244	229	862	544	499	436	423	422
			C	415	1220	2180	4340	5700	6400	259	230	245	215	228	239	286	239	226	215	221	237	377	268	271	239	232	211	755	601	545	488	375	372
			D	465	1340	2540	4740	6310	6500	310	273	282	265	262	256	344	273	295	252	244	217	443	344	295	240	220	201	930	705	584	435	367	335
	Mortar, 1:3 by weight, Potomac Sand	Compression, 2 by 4-in. cylinders	A	455	1590	2880	4690	5740	6000	217	259	262	248	275	254	253	227	236	211	225	222	364	248	272	208	221	220	700	448	400	358	383	405
			C	335	1100	1960	3460	4730	5590	209	208	220	171	189	209	231	216	203	171	183	207	305	242	243	191	192	184	609	550	490	389	311	325
			D	410	1090	1900	3790	5800	5730	273	222	211	212	241	226	304	222	221	202	224	191	390	279	221	191	202	177	820	574	437	348	337	295

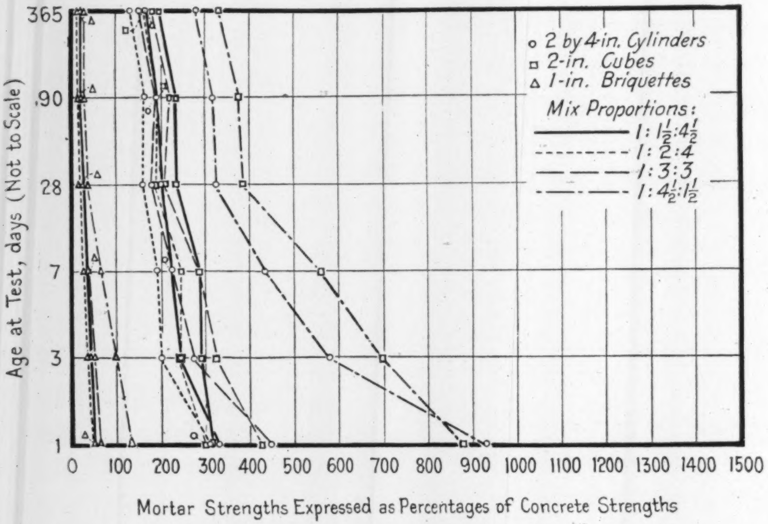

FIG. 5.—Strength Relations of 1:3 Standard Sand Mortars and Gravel Concretes of Different Proportions of Mix. Averages of Relations of Cements A, C and D with Coarse Aggregate of Grading K, which was Deficient in Small Sizes.

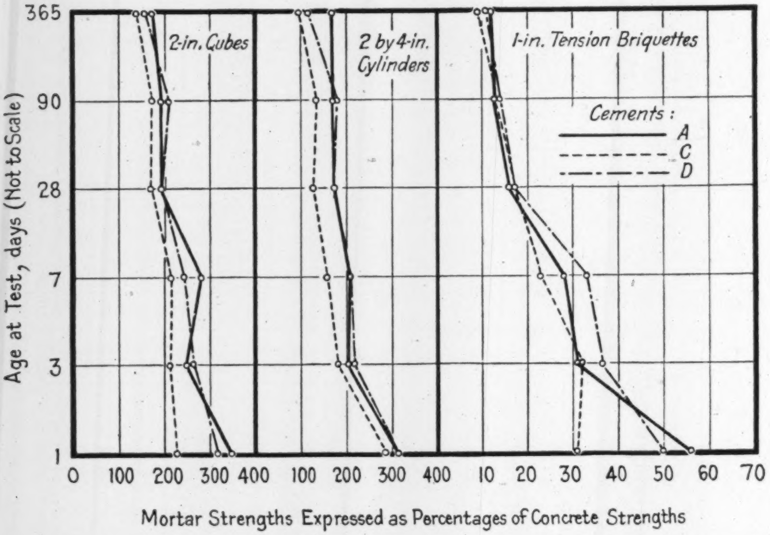

FIG. 6.—Strength Relations of 1:3 Standard Sand Mortars and 1:2:4 Gravel Concretes, Using Cements A, C and D with Gravel of Grading K, which was Deficient in Small Sizes.

In Fig. 4 comparisons are made of the mortar-concrete strength relations for cement B when used with gravel aggregate of three gradings, and employing three different porportions of mix in the concrete. (Data from Tables VI, VII and VIII.) Naturally, the ratios of mortar to concrete strengths change with changes in the make-up of the concrete which are of such nature as to affect the strength of the concrete. However, the interesting point is that, for any of the concretes, the ratios of the two compression mortar tests, while of somewhat different value, are closely alike in the trend of the lines joining the plotted values.

The discussion thus far has been on gravel concretes, since for such concrete only were there available sufficient data for comparison of the four cements. However, for cement B there are available strength data for concretes of three different proportions when using limestone and slag for coarse aggregates, the gradings and proportions being the same as used for the gravel concretes. The concrete strengths and the corresponding ratios are set forth in Tables VI, VII and VIII. No discussion is here offered on these crushed-aggregate concretes as related to mortar tests, except to remark that at any given age their strengths may vary considerably from that of the gravel concrete of similar proportions, that also their rate of change in strength with increase in age may be quite different from that exhibited by the gravel concrete.

Figure 5 shows the strength relations of mortars and concretes made with cements A, C and D, using four different proportions of concrete made with gravel of grading K, plotting the average values of cements A, C and D. (Data from Table IX.) For this gradation of coarse aggregate, and throughout the range of the mixes—under-sanded to over-sanded—it seems that the three different mortar specimens give indications of quite similar trends but of different values, which indications generally appear in approximately the same order of arrangement for the various mortar tests.

In Fig. 6 some of the data used for Fig. 5 are plotted so as to compare the relations of the mortar to the 1:2:4 concrete, showing separately the ratios for each of the cements A, C and D. This is somewhat of the nature of Fig. 3, illustrating that even for a widely different gradation of aggregate in the concrete, and a large variation in the workability of the mix, the relations of the mortar strengths to the concrete strengths exhibit the same general trend, but the values do not exactly coincide.

Estimates of the precision with which the strengths of concretes made with the different cements could be predicted from the mortar tests were made by the method of least squares for the 1:2:4 gravel concrete at the ages of 7 and 28 days. The correlations between the strengths of the concretes and the strengths of the mortars were in general better for the specimens made with Potomac River sand than for those made with standard sand and also the correlation was generally best with the 2-in. cubes. At 7 days the correlation was decidedly poorest for the briquets and at 28 days poorest to a less degree for the 2 by 4-in. cylinders.

SUMMARY

The curves showing the relation at several ages between the three types of mortar specimens and the several concretes are rather similar, but the values of the ratios showing these relations are in many cases far from identical.

The ratios of mortar to concrete strengths developed by the different cements varied with age, with kind of mortar specimens and with kind, grading, and proportioning of the concrete.

Since the grading and proportioning of the aggregate changes the strength of the concrete, it follows that the ratios of mortar strength to concrete strength will change with such alteration in the design of concrete.

As different kinds of aggregates also give different strengths in concrete, it follows that the same mortar-concrete strength relations will not hold for the several kinds of aggregates available.

Because of the above it is difficult to see from these tests how any ratio of the strength of any kind of mortar specimens to the strength of any concrete can be assumed as holding for the same concrete at all ages, or for all concretes at the same age. Rather all cements in one kind of mortar specimen develop a strength which has a certain ratio to the strength of the same cement in a certain concrete, but this ratio changes with ages of testing and with changes in kind, grading, and amount of aggregates.

As judged by the 7 and 28-day tests, the correlation between the strengths of the 1:2:4 gravel concretes and the strengths of the mortars were in general better for the specimens made with Potomac River sand than for those made with standard sand and also the correlation was generally best with the 2-in. cubes.

DISCUSSION

MR. E. M. BRICKETT[1] (*presented in written form*).—Mr. Dwyer and Mr. Bates have presented this paper on relations between the strengths of cements in mortars and in concretes with the expressed purpose of promoting discussion and study of the subject. The data which they offer picture their mortar tests as not very promising in ability to indicate performance of the respective cements in concrete. The earlier portion of this discussion will attempt to offer an explanation for the poor indicating qualities of the mortar tests used in these studies and the latter portion will be devoted to an account of some recent experiences we have had with the so-called plastic mortar test which seem to offer particularly promising possibilities.

In 1928 a paper was presented before this Society on "A Plastic Mortar Compression Test for Cement."[2] The plastic mortar test described in that paper was based primarily on the use of the same water-cement ratio in the mortar as was used in the concrete. The thought was expressed in that paper—and it will bear repeating here because it is evidently of prime importance in a study of indicator tests—that cements bearing certain strength relations to each other at one water-cement ratio do not necessarily bear these same relations at some other water-cement ratio. Subsequent investigation in our own laboratory has given rather definite evidence that this bit of theorizing is correct; that cements may bear quite different strength relations, one to another, at different water-cement ratios.

These tests by Mr. Dwyer and Mr. Bates merely offer further substantiation of the above statements. The concretes were fabricated with water-cement ratios ranging from 0.82 to 1.81, with nearly all of the ratios higher than 1.00. The standard sand mortars had water-cement ratios of approximately 0.61 and the Potomac River sand mortars had water-cement ratios of approximately 0.82. It is not surprising that the authors found that the mortar-concrete strength relations for the different cements were lacking in agreement.

The authors show that as the concrete proportions are changed, the strengths are affected accordingly and if we compare the strengths of these concretes with a given set of mortar strengths we are bound to get a variation in the strength ratios. This fact is obvious. It is also true that no specification test for cement can be devised which will anticipate all of the conditions under which the cement may be used. The best we can hope for is a test which will give a fair indication of the performance of a cement in a concrete representative of the most general use. The authors recognize this fact and in Table V they adopt the 1:2:4 concrete as a basis of study. It is necessary to go further and adopt a representative water-cement ratio before proceeding to the design of a suitable specification test.

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[1] **Engineer of Tests, Research Division, Lehigh Portland Cement Co., Allentown, Pa.**

[2] **E. M. Brickett, "A Plastic Mortar Compression Test for Cement,"** ***Proceedings*****, Am. Soc. Testing Mats., Vol. 28, Part II, p. 432 (1928).**

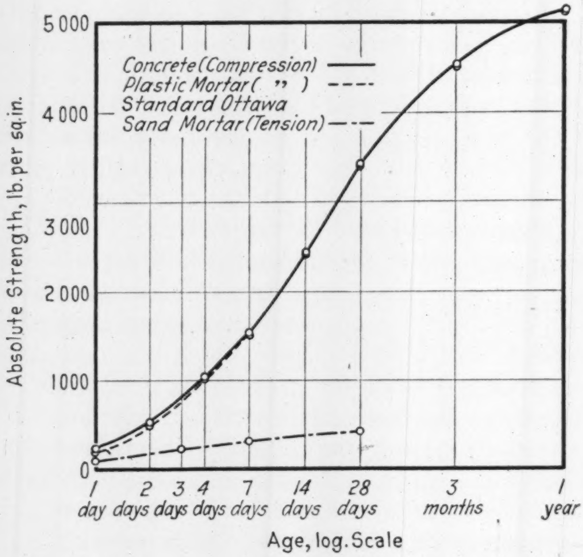

FIG. 1.—Grand Average Strengths in Concrete, in Plastic Mortar and in Standard Ottawa Sand Mortar.

There is every reason to believe that a plastic mortar specification test can be devised on the above basis and that it would be a far better indicator of the concreting qualities of cements than is the present standard mortar tension test. And even if a concrete of high water-cement ratio were involved it is most probable that a plastic mortar test as just proposed would give a better indication of the comparative performance of two or more cements in the concrete than would the present tension test, simply because the established water-cement ratio in the plastic mortar would be closer to that which would prevail in the field.

Recent work at the Central Laboratory of the Lehigh Portland Cement Co. has brought about improvements in the plastic mortar test, first described in the paper already mentioned, so that in its present state the test possesses many characteristics which recommend it for purposes of cement specification.

In the accompanying Fig. 1 are shown the absolute strengths for concrete cylinders, plastic mortar cubes and for standard Ottawa sand tension briquets for a series of cement tests extending over a period of five months. At one day the plastic mortar strength was 10.2 per cent below the concrete strength, at 2 days it was 6.7 per cent low, at all six subsequent ages up to one year, the plastic mortar strengths differed from the concrete strengths by less than 2 per cent.

TABLE I.—COMPRESSIVE STRENGTH IN CONCRETE AND PLASTIC MORTAR AND TENSILE STRENGTH IN STANDARD SAND MORTAR OF FOUR CEMENTS.

Age	Cement No. 1		Cement No. 2		Cement No. 3		Cement No. 4	
	Concrete	Mortar	Concrete	Mortar	Concrete	Mortar	Concrete	Mortar
COMPRESSION STRENGTH, CONCRETE AND PLASTIC MORTAR, LB. PER SQ. IN.								
1 day	180	173	167	168	330	292	673	643
2 days	500	483	571	523	712	731	1510	1330
4 days	1090	1060	1270	1280	1330	1280	2370	2260
7 days	1670	1690	1950	1940	1790	1760	3020	2810
14 days	2510	2580	3250	3030	2820	2740	3730	3730
28 days	3570	3710	3940	3990	3660	3640	4400	4350
3 months	4110	4490	4530	4500	4480	4270	4540	4600
1 year	4780	4920	4910	5010	4930	4980	5020	5150
TENSILE STRENGTH, STANDARD MORTAR, LB. PER SQ. IN.								
1 day	77		82		132		203	
3 days	230		227		280		367	
7 days	312		315		313		412	
28 days	408		455		428		422	

Because of this almost perfect coincidence of the plastic mortar and concrete strengths the plastic mortar curve in Fig. 1 is indicated only at the very early ages; an attempt to show both the concrete and the plastic mortar curves at the later ages would only lead to confusion with the scale employed. At these later ages the two curves may be considered as identical. The standard Ottawa sand mortar tensile strengths were determined at 1, 3, 7 and 28 days and are shown in the figure. Even a cursory examination reveals the inability of the standard tension test to indicate concrete performance. There is no similarity whatever in the shapes of the curves for concrete and for standard mortar. The standard mortar tension tests were not carried beyond 28 days. However, with a 28-day strength well above 400 lb. per sq. in. it is a foregone conclusion that the standard briquets could never show a gain commensurate with the concrete gain at the later ages because this test in its present form rarely shows a strength over 500 lb. per sq. in. This is one of the objectionable limitations of the present standard tension test. The briquet is of such shape and is held in such manner in the clips that localized stresses are induced when the load is applied. The stress across the reduced section of the briquet is not uniform and the failure is progressive, starting with tearing at the outer edges. The apparent strength calculated on the assumption of uniform distribution of stress across the section may be far below the actual stress at which failure started. In this present era of higher strengths in our cements this inherent limitation of the tension test is a condemning feature.

The data shown in Fig. 1 are, of course, average values covering five months of tests. They give but little information concerning the faithfulness of the plastic mortar test in indicating concreting qualities in individual cases. In the accompanying Table I there are shown the concrete and plastic mortar compressive strengths and the standard mortar tensile strengths for four experimental cements on which the three types of test were made. These four cements were chosen to illustrate certain inconsistencies of the present tension test; aside from that they were merely selected at random from the hundred or so cements on which we have made these three types of test.

Cements Nos. 1 and 2 were chosen because their tensile strengths at 1, 3 and 7 days were practically identical while there is a real difference in the concrete strengths. Cements Nos. 3 and 4 show progressively higher strengths than the first two cements, though their tensile strengths at the later ages fail to reflect the margin. A detailed study of the above data seems unnecessary here; anyone interested may make his own analysis on whatever basis appeals to him. Suffice it to note here that the tension test may be very misleading in its indications of concreting quality whereas the plastic mortar test follows the vagaries of the several cements closely. The degree of faithfulness with which the plastic mortar reflects concrete performance is attributed primarily to the use of a common water-cement ratio in the two tests.

There is no reason for feeling discouraged with the test results reported by Mr. Dwyer and Mr. Bates. They only serve further to bear out a contention which was expressed two years ago, that one of the prime essentials in an indicator test which is to portray concrete performance accurately is that it be made with a water-cement ratio commensurate with that used in the concrete. The plastic mortar test has been developed in our own laboratory to a point where the agreement in absolute strengths between mortar and concrete is within the limit of experimental error except possibly at the one- and two-day ages when the mortar strengths may be slightly lower than the concrete strengths as mentioned previously. On the basis of all this experience it seems but a short step, and a logical one, too, to a specification test which will provide an accurate indication of the performance of a cement in a representative concrete. To be sure, concretes in practice vary widely in proportions and in aggregates and the strengths must vary accordingly. A specification test which will indicate cement performance in a representative concrete should be considered a vast improvement over the present tension test, and even though such a standardized plastic mortar test would not indicate absolute strengths for concretes of varying proportions and consistencies, there is reason to believe that even in this case it would be a better indicator of the *comparative* concrete performance of cements than is the present tension test.

MR. H. F. GONNERMAN[1] (*presented in written form*).—This paper points out some of the difficulties encountered in devising an acceptance test for portland cement which will also be reasonably indicative of the strength behavior of different cements when used in concretes of approximately average properties. Subcommittee VII of the Society's Committee C-1 on Cement has been giving considerable attention to this question in recent years and a number of laboratories have been making tests along lines somewhat similar to those followed by Messrs. Dwyer and Bates.

The principal objections to the standard briquet test seem to be that in tests at early ages it gives relatively high strengths for cements which produce low strengths in concrete and relatively low strengths for cements producing high concrete strengths. Moreover, the retrogression in briquet strength which occurs at ages beyond 28 days or three months makes it unsuitable as an indicator of concrete strength at late periods and limits its value for research purposes.

Results of tests carried out recently in our laboratory on 6 by 12-in. concrete cylinders and on 2-in. plastic mortar cubes are of interest in connection with the studies reported by Dwyer and Bates. In our tests, cylinders were made of gravel concrete mixtures, the net water-cement ratios of which were 0.60, 0.80, and 1.00. For comparison with these concrete mixtures, 2-in. plastic mortar cubes were made from a graded Ottawa sand (proportions: 0 to No. 100, 15 per cent; No. 100 to No. 48, 20 per cent; No. 48 to No. 28, 25 per cent; No. 28 to No. 20, 40 per cent) as well as from standard Ottawa sand (passing No. 20 sieve retained on No. 30). The net water-cement

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[1] Manager, Research Laboratory, Portland Cement Assn., Chicago, Ill.

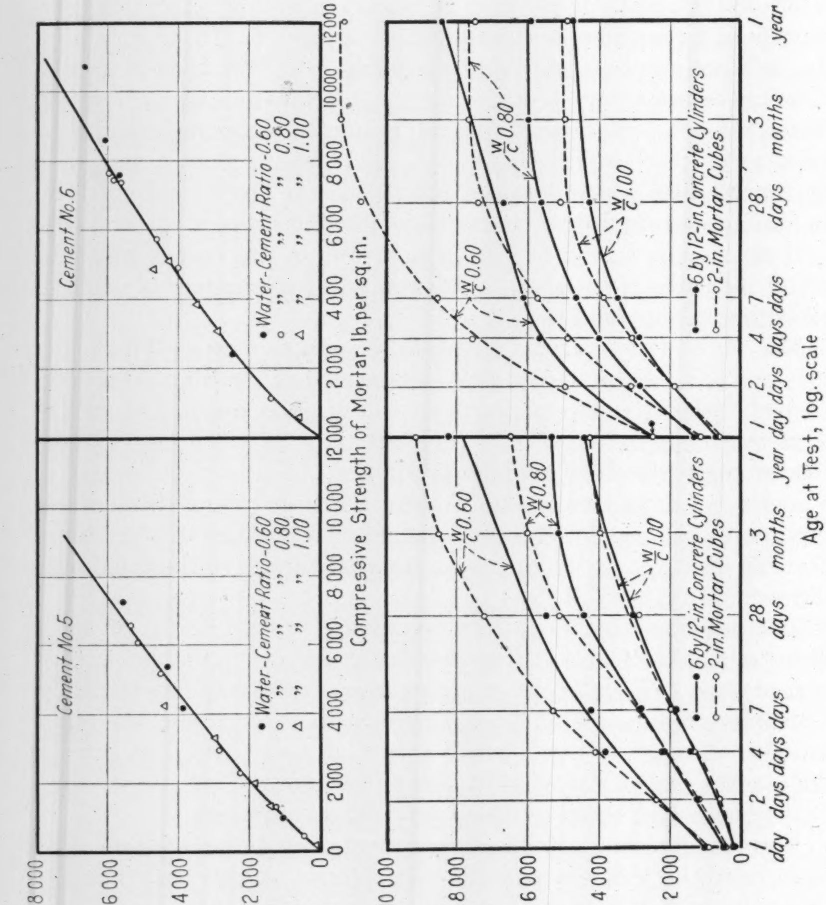

FIG. 2.—Showing Relation Between Strengths of 6 by 12-in. Concrete Cylinders and 2-in. Graded Ottawa Sand Mortar Cubes.

ratios of the graded sand mortars were the same as for the concrete while the water-cement ratios for the standard Ottawa sand mortars were 0.51, 0.67, and 0.80. The latter values were selected as giving approximately the same strengths respectively as the 0.60, 0.80 and 1.00 water-cement ratio concretes in accordance with results reported before the Society in 1929 by O. L. Moore.[1] Tests of both concrete cylinders and plastic mortar cubes were in general made at ages of 1, 2, 4, 7 and 28 days, 3 months and 1 year for 8 different portland cements of a fairly wide range in strength properties. The accompanying Fig. 2 shows results for cements Nos. 5 and 6 which are typical of those obtained with the other 6 cements.

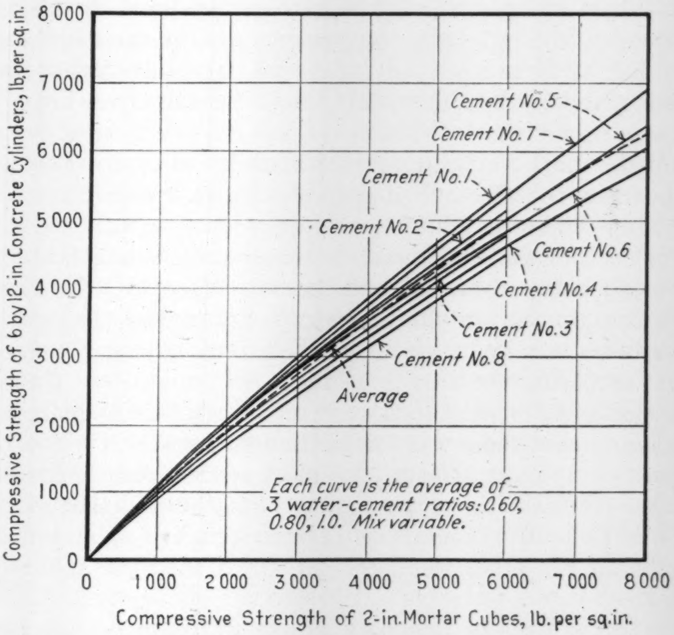

FIG. 3.—Strength Relations for Graded Ottawa Sand Mortar and Concrete of Same Water-Cement Ratio.

Comparison of the strengths of the 2-in. plastic mortar cubes of *graded Ottawa sand* with the 6 by 12-in. concrete cylinder strengths showed:

1. That the strengths of the cubes and the concrete cylinders were in close agreement *at all ages* where a water-cement ratio of 1.00 was used for both mortar and concret; for 4 of the 8 cements

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[1] O. L. Moore, "A Compression Test for Portland Cement," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 570 (1929).

the strengths were almost identical at the various ages of test, while for the other 4 cements the cube and concrete strengths were the same at ages up to 7 days but at later ages the cubes generally showed somewhat higher strengths.

2. Where a water-cement ratio of 0.80 was used in both the mortar and concrete there was generally close agreement between cube and mortar strength at ages up to 7 days but at later ages the mortar cubes showed higher strengths than the concrete cylinders.

3. Where a water-cement ratio of 0.60 was used for both mortar and concrete, the strengths were approximately the same at 1 and 2 days but at later ages the cubes had markedly higher strengths than the cylinders, the difference increasing with increase in age at test.

These results showed that as the age increased there was a tendency for the mortar cubes to gain in strength in comparison with the corresponding concrete cylinder, indicating that some factor related to the shape and strength of the compression specimen was involved.

For each of the eight cements tested there was a fairly definite relationship between mortar and concrete strength. In these tests the relationship was curvilinear and was not exactly the same for the eight cements as may be seen from the accompanying Fig. 3.

In comparing the results of the tests on *standard Ottawa sand plastic mortar cubes* with their corresponding concrete cylinder tests, it was found that there was fair agreement between the mortar cube and concrete cylinder strength for most of the cements tested where the water-cement ratio of the mortar was 0.80 and that of the concrete was 1.00. In comparisons of corresponding cube and cylinder strengths for the other water-cement ratios tried the agreement was not so good.

Further studies of this type of test will be necessary before an entirely satisfactory test procedure can be evolved. This method of testing cement appears to have advantages over the briquet test which justify giving it further consideration by Committee C-1.

MR. F. O. ANDEREGG.[1]—There need be no doubt about it, but this work with graded sand is a step forward. Each one of these gentlemen, who has spoken, has used some particular grading of sand.

Now there are many different gradings of sand available. If we were going to specify a certain grading, should we take an average of a large number of commercial sands, or should we find that sand which gives the ideal grading according to mathematical laws as confirmed experimentally, and take that as our standard for making tests on cements? With a sand such as Mr. Gonnerman speaks of, made up under one set of conditions our specimens were giving 2300 lb. per sq. in. compressive strength at 28 days, while with a sand such as was mentioned by Mr. Brickett, about 3500 lb. per sq. in., and with a stand that is graded more ideally still, about 6500 lb. per sq. in. for a 1:3 mix, all with the same cement.

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[1] Senior Industrial Fellow, Mellon Institute of Industrial Research, Pittsburgh, Pa.

MR. GONNERMAN.—The reason we used this particular grading in making the mortar specimens was to prevent segregation of the mixing water from the mixture. To accomplish this, we introduced into the sand mixture a considerable quantity of the finer sizes in order to hold the water in the specimen. One could use almost any grading provided no segregation occurred. We used the Ottawa sand because it can be purchased cheaply in the mine-run grading and has a very low absorption.

MR. R. L. BERTIN.[1]—I should like to ask Mr. Gonnerman why he used 2-in. cubes instead of 2 by 4-in. cylinders in his mortar tests?

MR. GONNERMAN.—In some investigations we used both types. Cubes do not require capping and therefore have an advantage over the cylinders. Capping introduces another undesirable element in the testing procedure and may cause large variations in the test results if not properly done. Subcommittee VII has considerable data on hand which show that cylinder strengths are much more variable than cube strengths under given conditions of test. The cube is turned on its side when put into the testing machine for loading. By making the molds with accurately machined plane surfaces we obtain specimens which do not require capping. This saves considerable time in testing and also insures obtaining an even distribution of load over the specimen.

MR. BERTIN.—While the use of the cube is more convenient, I wonder whether its strength can be compared directly with that of 6 by 12-in. cylinders. I notice in Messrs. Dwyer and Bates' paper that a considerable difference exists between the compressive resistance of 2 by 4-in. cylinders and that of 2-in. cubes made from the same mortar.

MR. GONNERMAN.—The point that Mr. Bertin brought out is well taken. We are investigating the relationship between the strengths of 2-in. cubes and 2 by 4-in. and 6 by 12-in. cylinders where the same mortar is used for all three types of specimen. No doubt we will find a difference in the strengths of the three types of specimen. That is one of the points on which we are trying to obtain information in connection with our investigations of methods of testing cement.

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[1] Chief Engineer, White Construction Co., New York City.

MR. BAILEY TREMPER[1] (*by letter*).—The purpose of this paper as outlined in the opening paragraph is to present data having a bearing of the development of a satisfactory acceptance strength test for cement. The authors' discussion brings out the unsatisfactory results obtained with the standard briquet. It does not appear, however, that they have given sufficient emphasis to the fact that compression tests of the Potomac sand mortars are shown to be fairly accurate indicators of concrete strengths.

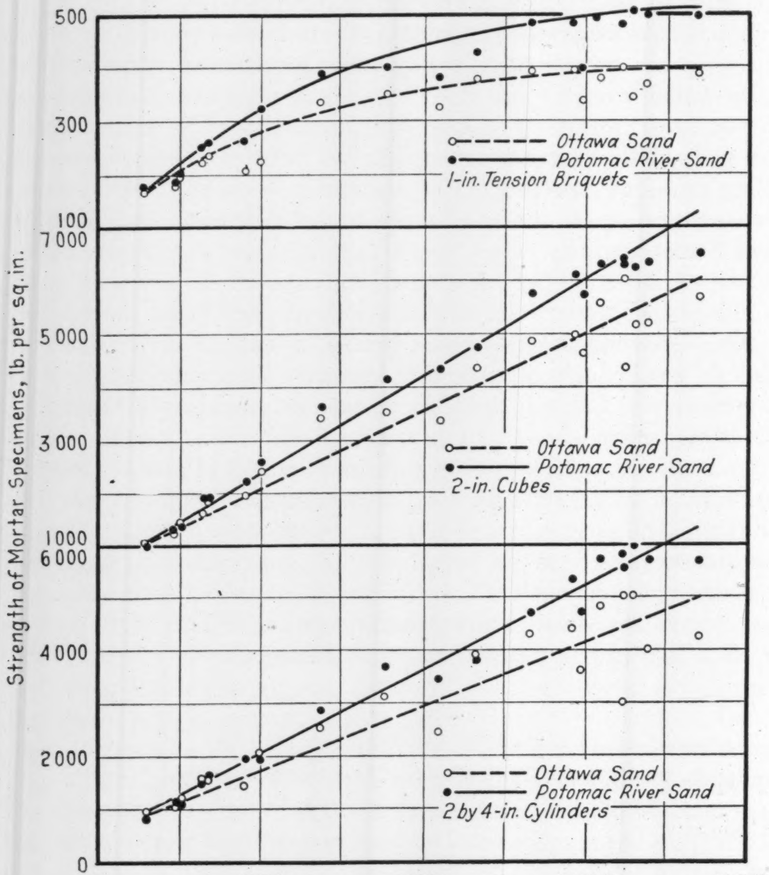

FIG. 4.—Showing Relation of the Strength of Each Kind of Mortar Specimen to the Strength of 6 by 12-in. Cylinders.

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[1] Engineer of Tests, State of Washington Division of Highways, Olympia, Wash.

Much of the data presented deals with tests of various concretes in which only one cement is used. This information does not aid greatly in determining the value of mortar test specimens as a criterion of the concrete strengths obtainable with various cements. Table V contains valuable data bearing on the subject outlined. The balance of the data either does not afford a comparison between different cements or, as in Table IX, gives results of concrete mixes that are not suitable for actual use.

In the accompanying Fig. 4 there is plotted the strength of each kind of mortar specimen against the strength of the 6 by 12-in. concrete cylinders, using the average results of gradings B, F and I in the 1:2:4 mix of gravel. The data are from Table V. The results of the three gradings were averaged to give a slightly greater accuracy to the concrete strength values. The one-day tests have been omitted because of the difficulty of clearly plotting the low values.

The curves indicate essentially a linear relationship for the compression specimens, whereas the briquets do not adequately express the higher strength concrete values. The Potomac River compression specimens are closer to the average curve than are those of Ottawa sand, particularly for the higher strengths. It appears to the writer that the authors' discussion does not clearly bring out these features. Tests by Brickett[1] have shown that under certain test conditions compression tests of graded sand mortars are very accurate indicators of concrete strengths of cements. In the laboratory of the Washington State Department of Highways similar studies have been extended to include high-early-strength cements as well as standard cements. We have found that the relationship between mortar tests and concrete strengths can be expressed with considerable accuracy by a single curve throughout the entire range of cements and concrete strengths up to 6000 lb. per sq. in. The essential condition is that mortar and concrete tests be made with the same water-cement ratio. Had this condition been met in the authors' work it is believed that there would have been less variation between the plotted points and the average curve.

In Table V the 6 by 12-in. concrete specimens were made with water-cement ratios of from 1.01 to 1.10 whereas in the accompanying mortar tests the ratios were approximately 0.61 and 0.83. It so happened that with the four cements used there was little difference among them with respect to their water requirements either as judged by normal consistency or by flow table tests.

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[1] E. M. Brickett, "A Plastic Mortar Compression Test for Cement," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 432 (1928).

In our laboratory we have found that there is a considerable variation in the water requirements in concrete of different cements, particularly if high-early-strength cements are included. Unless the water used in mortar tests is made to vary accordingly their indications are apt to be in error to an important degree. The standard normal consistency test is not sufficiently indicative of concrete consistency. The most satisfactory method we have devised for proportioning water is to determine the quantity required in a standardized concrete mix of a given slump and to use this water-cement ratio in mortar tests.

By the use of this method, we are able to get good results not only with graded sand but with Standard Ottawa sand in approximately a 1 : 2¼ mix and a consistency of about 110 per cent of standard mortar. The water-cement ratio we have used has been in the neighborhood of 0.60. These tests have included concrete strengths of 6000 lb. per sq. in. and upwards but we are not yet sure whether reliable results can be obtained for test ages of one year and over.

There seems to be a general tendency to base strength of cements on concrete having water-cement ratios of about 1.00. Our tests indicate that this ratio is not always very accurate for judging cement to be used in higher strength concrete. It is probably desirable to use not more than one water-cement ratio in cement testing and it seems more logical to use a low ratio, say 0.6 or 0.7, since the higher strength concretes are more difficult to produce and more accurate control of materials is necessary.

It is concluded that a compression test of mortar can be standardized so that the results can be translated directly and with considerable accuracy into a relative concrete strength of any cement without regard to age of test. With such a test it is possible to estimate the percentage difference in concrete strengths of two cements or to determine at what ages two cements will produce concretes of equal strengths.

MR. H. J. GILKEY[1] (*by letter*).—The authors state that the data presented were obtained in the course of another investigation. It requires little study to recognize that the main investigation evidently contemplated, among other things, a rather basic study of the effect of grading as well as kind of coarse aggregate upon strength.

Adequate detail for study from consistent, well planned, and dependable projects are so rare that the writer was unable to refrain from scanning these data for any light they might throw upon some aspects of concrete that have been stimulating his curiosity for a number of years. In the main the points to be discussed are somewhat aside from the phases to which the paper has been intentionally restricted. Without wishing to detract from the very important points brought out, the writer feels that the present paper contains much that is intimately related to the subject of Ira L. Collier's paper on "Variations of Compressive Strength of Concrete Within the Water-Cement Ratio Law,"[1] and also to Mr. F. R. McMillan's Appendix III to the current report of Committee C-9 on Concrete and Concrete Aggregates.[2] This discussion is referred to in connection with discussions of the two papers mentioned.

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[1] Professor of Civil Engineering, University of Colorado, Boulder, Colo.

TABLE II.—DATA FOR GRADINGS K AND L; CEMENTS A, C, AND D.

All gravel concretes—Grading K, $\frac{3}{8}$ to $1\frac{1}{2}$ in.; Grading L, $\frac{3}{4}$ to $1\frac{1}{2}$ in.
Potomac River Sand, 0 to 4.
Fineness modulus of sand, 2.87.
Surface modulus of sand, 21.17.

	Cement	Fineness Modulus[a]	Surface Modulus[a]	Water-Cement Ratio[b]	28-day Compressive Strength, lb. per sq. in.[c]	Theoretical Strength (Abrams'), lb. per sq. in.[d]	Strength Ratio[e]
		1	2	3	4	5	6
MIX $1:1\frac{1}{2}:4\frac{1}{2}$:							
Grading K........	A	6.34	5.74	0.97	1890	2100	0.90
	C	6.34	5.74	0.94	1570	2240	0.70
	D	6.34	5.74	0.94	1840	2240	0.82
Grading L.........	A	6.72	5.59	0.89	1890	2460	0.77
	C	6.72	5.59	0.86	2020	2620	0.77
	D	6.72	5.59	0.87	1790	2570	0.70
MIX 1:2:4:							
Grading K........	A	5.96	7.46	1.02	2480	1920	1.29
	C	5.96	7.46	1.00	1940	2000	0.97
	D	5.96	7.46	1.00	2220	2000	1.11
Grading L.........	A	6.29	7.32	0.96	2220	2160	1.03
	C	6.29	7.32	0.93	2020	2290	0.88
	D	6.29	7.32	0.95	1880	2200	0.86
MIX 1:3:3:							
Grading K........	A	5.19	10.88	1.22	2280	1300	1.75
	C	5.19	10.88	1.22	1740	1300	1.34
	D	5.19	10.88	1.21	2020	1330	1.52
Grading L.........	A	5.44	10.78	1.19	2250	1380	1.63
	C	5.44	10.78	1.17	1810	1440	1.26
	D	5.44	10.78	1.17	1980	1440	1.38
MIX $1:4\frac{1}{2}:1\frac{1}{2}$:							
Grading K........	A	4.03	16.03	1.64	1210	570	2.12
	C	4.03	16.03	1.63	930	580	1.61
	D	4.03	16.03	1.61	1120	610	1.84
Grading L.........	A	4.15	15.98	1.60	1310	620	2.11
	C	4.15	15.98	1.61	890	610	1.46
	D	4.15	15.98	1.60	1090	620	1.76

[a] Computed from data of Table III.
[b] From data of Table IV.
[c] From data of Table IX.
[d] $S = \frac{14000}{7^x}$, see H. J. Gilkey, "Water Tables and Curves for Use in Designing and Estimating Concrete Mixtures," *Proceedings*, Am. Concrete Inst., Vol. XXV, p. 292 (1929).
[e] Actual strength divided by theoretical strength at same water-cement ratio.

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[1] See p. 731.

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 521 (1930).

Table IV of the paper supplies an excellent schematic view of the project. Using Tables IV and III the following facts are apparent.

1. In gradings B, F and I the quantities of both coarse and fine aggregate are varied in the same direction and the ratio of coarse to fine is kept at two throughout. This makes the fineness modulus and surface modulus constant for all the concretes from a given grading although the proportion of cement to total aggregates varies from 1:4½ to 1:9.

2. The fineness moduli[1] for the mixed aggregates B, F and I are 5.29, 5.73, and 5.40, respectively.

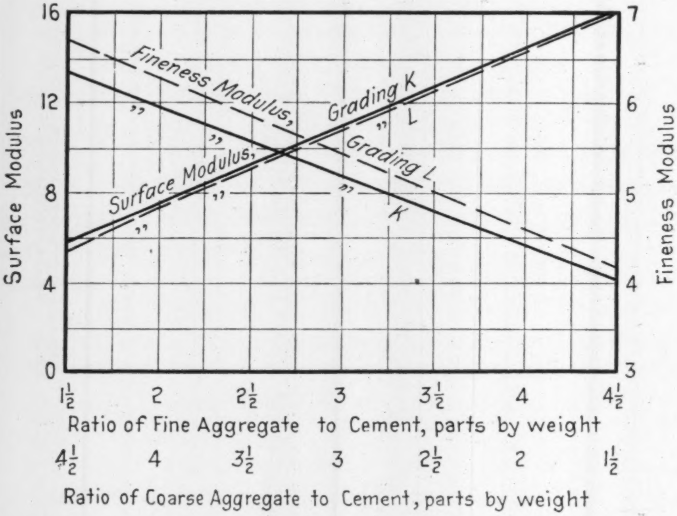

FIG. 5.—Showing the Relation of Fineness Modulus and Surface Modulus to Proportions of Aggregate for Gradings K and L.

3. The surface moduli for the mixed aggregates B, F and I are 7.84, 7.59, and 7.80, respectively.

4. For gradings K and L the ratio of total aggregate to cement is held constant at six but the ratio of fine to coarse is varied. This means that the fineness modulus and surface modulus vary with every different mixture. Values are given in the accompanying Table II (columns 1 and 2). It is also apparent from the accompanying Fig. 5 that for each of the two gradings K and L, both the fineness modulus and the surface modulus bear a straight line relationship to the proportions of the aggregates. The surface modulus increases directly

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[1] A. N. Talbot and F. E. Richart, "The Strength of Concrete; Its Relation to the Cement, Aggregates and Water," *Bulletin No. 137*, University of Illinois, p. 21.

with the sand ratio and the fineness modulus decreases. Grading L is somewhat coarser than grading K for each proportion.

5. On account of the added coarseness of grading L, a lower water-cement ratio was used to obtain workability comparable with that used in the concretes from grading K.

6. To summarize, it is evident that (*a*) gradings B, F and I were selected, in part, to obtain comparisons at constant grading and at a variable total aggregate-cement ratio and that (*b*) gradings K and L were selected, in part, to observe the effect of variable grading at a constant total aggregate-cement ratio.

This discussion will be largely restricted to a study of the 28-day compressive strength results of the specimens of the K and L gradings.

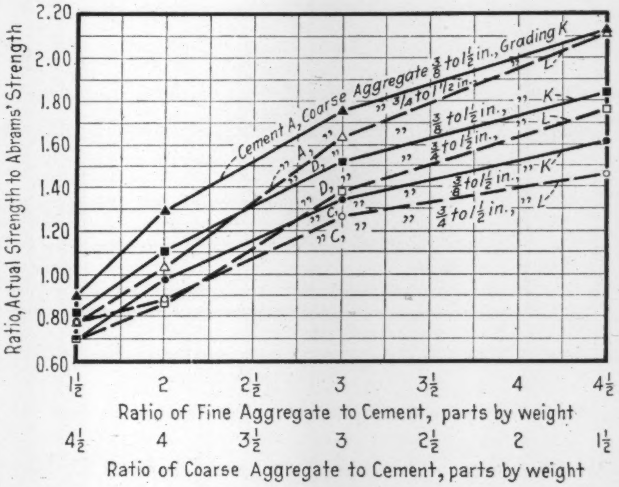

FIG. 6.—Showing the Relation of Strength Ratio to Proportion of Aggregate.

In attempting to study these results it is at once apparent that both the grading and the water-cement ratio are variables over wide limits. This difficulty is bridged by a method similar to one previously used.[1,2] The accompanying Table II, column 4, gives the actual strengths of the concretes while the theoretical strengths according to the Abrams relation are also listed in column 5. The ratios of actual strength to theoretical strength supply the evidence as to whether the performance was parallel to that indicated by the so-called law that expresses the relation between strength and water-cement ratio. The strength ratios appear as column 6.

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[1] H. J. Gilkey, "A Method for Predicting Concrete Strengths with Increased Precision," *Proceedings*, Am. Concrete Inst., Vol. XXIV p. 149 (1928).

[2] H. J. Gilkey, "Water Tables and Curves for Use in Designing and Estimating Concrete Mixtures," *Proceedings*, Am. Concrete Inst., Vol. XXIV p. 292 (1928).

If the concrete performed in accordance with its water-cement ratio as expressed by the Abrams equation, then the strength ratios (column 6) should be approximately constant.

The strength ratios as shown in column 6 of the accompanying Table II and Figs. 6, 7, and 8 are very striking. In every case the strength builds up from a value well below that given by the Abrams relation to one that is from 1.46 to 2.12 times the Abrams strength. Moreoever the rise is gradual, consistent, and positive. These data constitute a most forceful demonstration that the water-cement ratio alone does not tell the whole story. In this project the same findings are six times verified. There are two gradings each for three cements; yet in the whole group there is not a single inconsistent value.

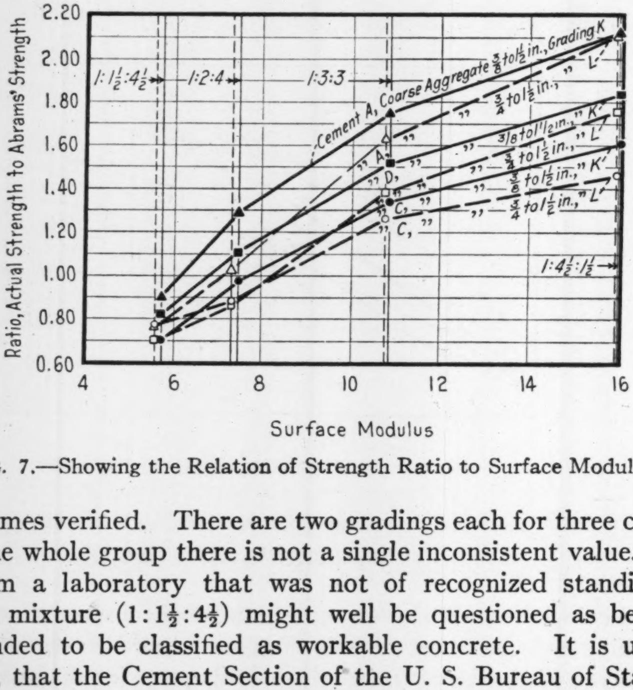

FIG. 7.—Showing the Relation of Strength Ratio to Surface Modulus.

From a laboratory that was not of recognized standing, the harshest mixture (1:1½:4½) might well be questioned as being too undersanded to be classified as workable concrete. It is unlikely, however, that the Cement Section of the U. S. Bureau of Standards would be reporting results from honeycombed specimens. Moreover there is no change in slope or erratic portion of any of the curves of the accompanying Figs. 6, 7, and 8 that would indicate a transition from unworkable to workable mixtures. With proper use and grading, placeable concrete can be obtained at a 1:3 sand to stone ratio and it is proper to assume that it was obtained in this case.

Referring to the accompanying Fig. 5, it is apparent that:

1. The surface modulus and proportion of sand vary directly as one another.

2. The fineness modulus and coarse aggregate ratios vary inversely with the sand ratio.

3. The important factor in determining the surface modulus is the fine aggregate since surface areas multiply rapidly as sizes of particles decrease. The coarse aggregate in these tests has very little influence on the surface modulus of the mixed aggregate. For example, the surface modulus of the sand is 21.17 while those for the coarse aggregates of gradings K and L are 0.59 and 0.39, respectively. The difference between gradings K and L is solely a matter of coarse aggregate grading. Figure 5 shows how little this difference amounts to in the case of surface modulus.

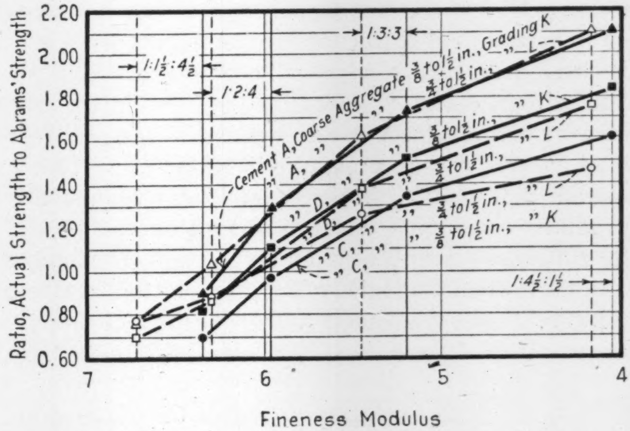

FIG. 8.—Showing the Relation of Strength Ratio to Fineness Modulus.

4. On the other hand the coarse aggregate grading and proportion exercises a very important influence upon fineness modulus. The fineness moduli of sand and gradings K and L, respectively, are 2.87, 7.50, and 8.00. Figure 5 shows the relatively greater influence that the difference in coarse aggregate gradings K and L has on the fineness moduli of the mixed aggregates.

5. With four straight-line variables (proportion of sand, proportion of stone, fineness modulus and surface modulus), it would be difficult to predict which might exercise the dominant influence for a case in which they were not all directly related to one another. Two or more might well be expected to produce a mixed effect. Surface and fineness moduli do not normally bear a straight line relationship to one another. A constant value of one may cover a considerable range of values for the other. Moreover simultaneous dif-

ferences in grading and aggregate proportions could greatly distort the straight line relationship of Fig. 5.

6. In support of the statements made above, the results from the tests for gradings B, F and I (constant fineness and surface moduli but variable ratios of cement to total aggregate) show consistently uniform strength ratios for the gravel concretes but the ratios vary from 1.04 to 1.59 for the slag concrete, with the limestone concrete intermediate between gravel and slag. The different gradings B, F and I seem to exercise considerable influence but the lowest strength ratio is for the 1:2:4 mixture in every case but one (and practically so for it).

7. It is obvious that Figs. 6 and 7 are virtually identical. For these concretes (gradings K and L) the proportions of sand and the surface moduli could be interchanged, that is the horizontal scales could be interchanged and scarcely alter the figures.

8. The strength ratio is lower for the coarser grading (grading L) in every case in Figs. 6 and 7. Since the variation in the grading was accomplished by changing the coarse aggregate only, and since such a change had a negligible effect upon the value of surface modulus, it is reasonable that plotting the strength ratio against the surface modulus produces a negligible effect in this instance.

9. The difference between gradings K and L is more nearly taken account of when strength ratios are plotted against fineness moduli (Fig. 8). This is reasonable in view of the fact that the change in coarse aggregate grading materially effects the values of the fineness modulus.

10. While not taking exception to any of the conclusions offered, the writer's observations are such as to make him agree most heartily with the third, fourth and fifth paragraphs of the summary. An effort was made to coordinate the 1:3 mortar 28-day compressive strength results on the 2 by 4-in. cylinders with the results of the concrete tests for cements A, C, and D. The water-cement ratio for the standard sand mortars was 0.61 while that for the Potomac River sand was 0.83. This fact should not be lost sight of in comparing the resultant strengths. The fineness and surface moduli were 2.99 and 12.60 for the standard sand and 2.87 and 21.17 for the Potomac River sand. The strength ratios for the Potomac River sand greatly exceeded those for the standard sand. The surface moduli took a reasonable account of the difference but the fineness moduli (being practically equal for the two sands) took almost no account of the differences in strength ratios. The strength ratios differed materially from those for the concretes when the comparison was on the basis of both fineness and surface modulus, although it paralleled them for the latter, but the strength ratios for the three

cements were in the same order for all mortars and for all the concretes (cement A, highest; cement D, next; and cement C, lowest). In comparing the several mortar acceptance type of tests with the concrete strengths, it is evident that there are differences that cannot as yet be explained fully. The variables in addition to those to which attention has been directed (water-cement ratio, fineness modulus and surface modulus) may be basic or they may be accidental. By accidental is meant such items as differences in making or testing technique, storage, size of specimen, etc. By basic is meant as yet unrecognized differences that may be inherent in gradings, proportions or other fundamental properties of the aggregates or mixtures.

The evidence of this paper seems to add support to the following generalizations, several of which the writer and others have advanced on previous occasions:

1. While the water-cement ratio may be an excellent compressive strength criterion for mixtures that resemble those from which the relation was experimentally determined[1] it is likely to be greatly in error if used without qualification as a basis for the comparison of mixtures the gradings of which differ widely. For given materials each different grading has its own water-cement ratio - strength relation.

2. At constant water-cement ratio the strength is greatly influenced by the grading. The smaller the grading, the greater the strength.[2] From this it follows that: (*a*) *a mortar should be stronger*

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[1] Usual mixtures invariably have ratios of course to fine aggregate of from 1.5 to 2.0. Within this range fall all such mixtures as 1:1:2, $1:1\frac{1}{2}:3$, 1:2:4, $1:2\frac{1}{2}:4$, 1:3:5, 1:3:6, 1:4:6, etc., and the size is below $1\frac{1}{2}$ in. For given materials the ratio of coarse to fine aggregate determines the grading of the mixture regardless of the quantities used. The limits of 1.5 to 2.0 are very narrow and the factors that depend upon differences in grading are therefore quite constant. These tests do not supply conclusive evidence regarding the effect of variation in the aggregate-cement ratio at constant grading and at constant water-cement ratio. Gradings B, F and I supply mixed evidence upon this point (see conclusion No. 6 above). While some of the writer's work seems to indicate that the strength is reduced as the total aggregate ratio is increased, at constant water-cement ratio, this trend if present is much less pronounced than is that due to grading. Collier's tests (*loc. cit.*, Table I and Fig. 3) indicate a slight trend in the opposite direction. The writer grants that this may well prove to be the case. Moreover the Abrams or other similar curve has this variable present since any appreciable increase in aggregate-cement ratio requires a corresponding increase in water-cement ratio. Thus a water-cement ratio of 1.00 might give a moderately stiff 1:2:4 concrete but a 1:3:6 concrete of the same grading might well require a water-cement ratio of 1.2 to be workable at all.

[2] This fact has been often obscured by the opposing fact that the finer the grading, the greater the water requirements. Thus less water will suffice to give needed workability to a coarsely graded mixture and the strength may exceed that of concrete from a finer aggregate mixed with more water. Probably it is this inverse effect of water and grading that has contributed largely to a widespread belief that strength increases with coarseness of aggregates (or with increase in fineness modulus). The extra water requirement for the finer grading (grading K) is readily apparent in Table II, column 3. In most cases the strength reduction due to the extra water does not quite offset the strength gain due to the finer grading. The ultra-practically minded individual might well ask the question, "If the finer grading requires enough extra water to produce the weaker concrete, why should one be concerned with whether it is the water or the finer grading that did it? Let us quit quibbling and focus upon essentials." The answer is that the first essential is to find out the "why" since it is a lack of this same fundamental knowledge that may lead to the performance of a dangerous exterpolation of what is in some cases a harmless pair of variables that accomplish a mutual cancellation.

than its concrete,[1] (*b*) *concrete with cobbles added should be weaker than the same concrete without the cobbles.*[2, 3, 4]

3. There is no question as to the economy from the standpoint of yield, of gradings, the larger sizes of which approach the limit of what can be economically placed or which are not too large in comparison with the minimum cross-sectional dimensions of the structure (usually one-fourth the diameter or least dimension of mold or form). Nevertheless the indications are that such concrete will be less strong than will concrete of exactly the same water-cement ratio but which has a lower fineness modulus (finer grading of aggregate). If tests have determined reasonable values for relative strengths of such mixtures it may then be proper to pick out the cobbles, apply a reduction coefficient to the strength obtained and consider the result to be the probable strength of the cobble concrete. Unless the evidence of this paper and that from other tests of which the writer knows,[1, 2, 3, 4, 5, 6] that have a *direct bearing* upon the subject are grossly in error, it is incorrect and on the unsafe side to pick out the cobbles and assume that the resulting strength is that of the cobble concrete.

4. In comparing concretes of different gradings it appears that the fineness modulus may be the fairer measure of grading differences if the difference is mainly in the coarse aggregate. If the difference in grading is mainly in the fine aggregate it would appear that the surface modulus may be expected to prove the better measure of grading differences. For constant sand and coarse aggregate, the grading becomes coarser as the sand ratio is decreased and *vice versa*. The fineness modulus is raised rapidly as cobbles are added but the surface modulus is little influenced except as the sand ratio is thereby reduced.

Much illuminating discussion pertaining to the grading of aggregates will be found in papers and discussions by L. N. Edwards, D. A. Abrams, R. B. Young and others in the *Proceedings* of the Society for the period 1917 to 1919.

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[1] H. J. Gilkey, with discussion by H. F. Gonnerman, G. M. Williams and others, *Proceedings*, Am. Concrete Inst., Vol. XXIII, pp. 363-414 (1927).

[2] I. E. Burks, "Concreting Methods at Chute a Caron Dam," *Proceedings*, Am. Concrete Inst., February, 1930, p. 353.

[3] H. J. Gilkey, Discussion of paper by I. E. Burks, "Concreting Methods at Chute a Caron Dam," *Proceedings*, Am. Concrete Inst., June, 1930, pp. 883–886.

[4] F. R. McMillan, "Suggested Procedure for Testing Concrete in Which the Aggregate is more than One-Fourth the Diameter of the Cylinders," Report of Committee C-9, Appendix III, *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 521 (1930). See also discussion by H. J. Gilkey of above paper.

[5] Ira L. Collier, "Variations of Compressive Strength of Concrete Within the Water-Cement Ratio Law," see p. 731.

[6] T. C. Powers, "Concrete Studies at the Bull Run Dam," *Proceedings*, Am. Concrete Inst., Vol. XXV, p. 390 (1929).

MESSRS. J. R. DWYER[1] and P. H. BATES[2] (*authors' closure by letter*).—It was realized that the water-cement ratio was not the same for the mortars and concretes, and it was stated that the data, incidental to another investigation, were not sufficient for very definite conclusions but were offered primarily to stimulate discussion. Certainly, there was no intention of discouragement, although attention was particularly invited to the unsatisfactory indications of the mortar tests reported, since the standard sand mortars were made in accordance with current portland cement specifications, and the Potomac sand mortars were made of a consistency apparently similar to that of the standard sand mortars, as would be done in some of the current practice.

There was no desire to detract from certain of the desirable features of the more plastic mortars, such as described by Mr. Brickett. Indeed, such plastic mortars well merit consideration, even though some of them as now made, as stated by Mr. Brickett, may show a slight variation in the mortar-concrete strength ratio over a one-year period.

While obvious that the mortar-concrete strength relations would necessarily vary with certain variations in the concrete make-up, yet the strengths of the various concretes were given to afford readers an opportunity of comparing mortars with concrete made with various aggregates and in different proportions.

The discussions serve well to emphasize the apparent shortcomings of the present standard tension test, in so far as judged by concrete strengths.

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[2] Chief, Clay and Silicate Products Division, U. S. Bureau of Standards, Washington, D. C.

STRENGTH AND RESISTANCE TO SULFATE WATERS OF CONCRETE CURED IN WATER VAPOR AT TEMPERATURES BETWEEN 100 AND 350° F.[1]

By Dalton G. Miller[2]

Synopsis

The conclusions of the paper relative to concrete cured in water vapor are based on experiments that began in 1922 from which it was learned that curing conditions may very greatly influence the resistance of concrete to sulfate waters. Some twelve thousand 2 by 4-in. concrete cylinders have been made and many already tested. The type of concrete has been limited to that suitable for average size drain tile and with this in mind, particular attention has been given to studies to determine the influence on compressive strength and resistance to sulfate waters of the following variables:

1. Temperatures between 100 and 350° F. of water vapor in which the concrete was cured,
2. Duration of curing periods up to 32 days, and
3. Portland cements from 14 different mills.

The data indicate that variations between 100 and 350° F. in the temperature of the water vapor in which the concrete was cured have relatively small influence on the strength of the concrete although they do have a very positive influence on resistance to sulfate waters. The reaction of portland cements from different mills to curing under these special conditions has been essentially similar.

Introduction

Steam has been used for many years in the curing of drain tile, partly to accelerate hardening and partly to maintain humidity at temperatures well above freezing during cold weather. The boilers used generally operate under low pressures and rarely do the temperatures in a curing room rise above 135° F. This is ordinarily referred to as "steam curing" although at no time do the curing temperatures approach that of boiling water. In this report all temperatures indicated are those to which the specimens were actually subjected during curing and with but one, or at most two, exceptions are

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[1] University of Minnesota *Paper No. 940,* Journal Series. Results of experiments at University Farm, St. Paul, Minn., in the Drain Tile Laboratory conducted by the Department of Agriculture of the University of Minnesota, the Department of Drainage and Waters of the State of Minnesota and the U. S. Department of Agriculture.

[2] Senior Drainage Engineer, U. S. Bureau of Public Roads, University of Minnesota, St. Paul, Minn.

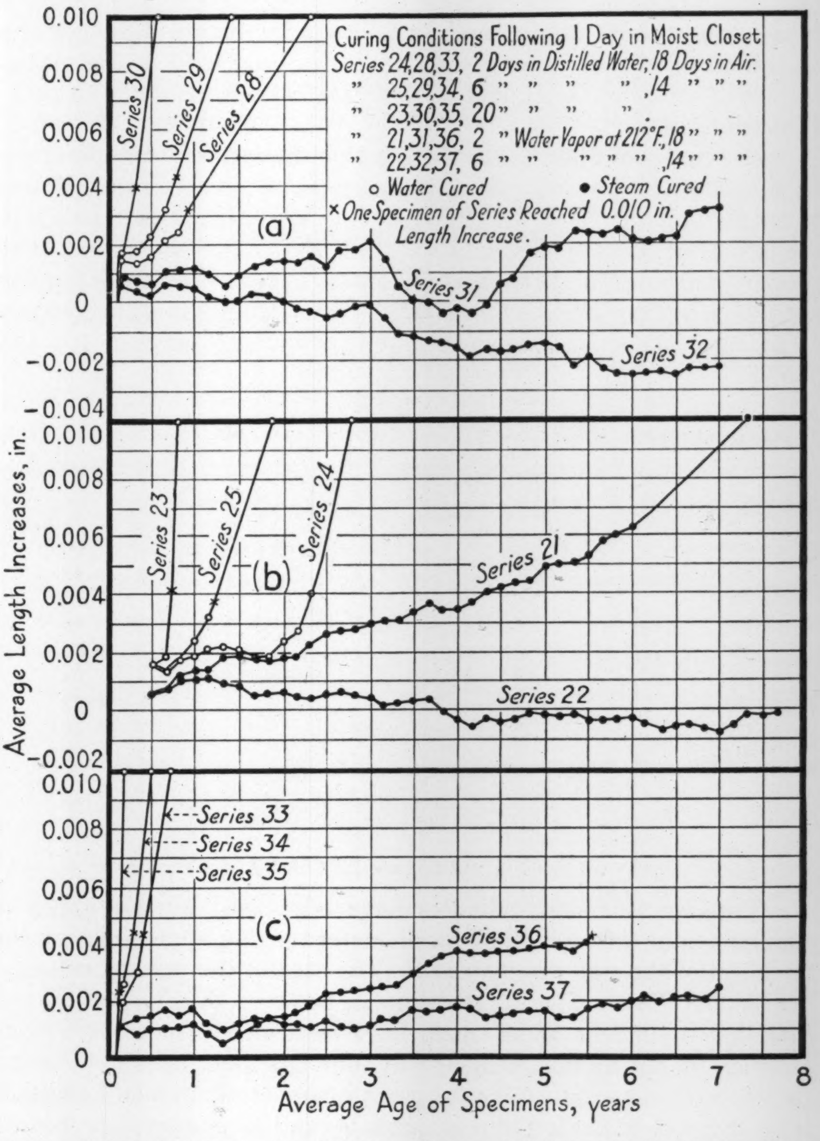

FIG. 1.—Influence of Curing Conditions on Change of Volume of 2 by 4-in. Portland-Cement Mortar and Concrete Cylinders, 1:3 Mix, Stored in Sodium Sulfate and Magnesium Sulfate Waters.

(*a*) Concrete stored in 1-per-cent solution of sodium sulfate.

(*b*) Concrete stored in 1-per-cent solution of magnesium sulfate.

(*c*) Ottawa sand mortar stored in 1-per-cent solution of magnesium sulfate.

Length increase of 0.10 in. is indicative of 50 to 70-per-cent loss in compressive strength.

Each point is average for 5 or 10 cylinders made on 5 different days.

considerably above those used at commercial plants although the maximum of 350° F. is no greater than has been used in the manufacture of sand-lime brick and is, therefore, within the limits of practical application.

The curing of drain tile and other pipe that after installation may be subjected to the action of soil alkalies in which occur the sulfates of magnesium ($MgSO_4$) and sodium (Na_2So_4) often does not receive the attention that its importance has been found to merit. The primary purposes of the work here reported have been to determine both the effect on strength and the effect on resistance to sulfate waters of curing concrete in water vapor at temperatures between 100 and 350° F.

TABLE I.—AVERAGE OF FOUR ANALYSES OF WATER FROM MEDICINE LAKE, S. DAK. Analyses by the Water and Beverage Laboratory, Bureau of Chemistry, U. S. Department of Agriculture

RADICAL	ANALYSIS, MG. PER LITER (PARTS PER MILLION)	REACTING VALUES, PER CENT
Na (Calculated)	3 036	10.38
Ca	717	2.93
Mg	5 079	36.69
NO_3	1	0.01
Cl	509	1.01
SO_4	27 021	48.22
CO_3	88	0.30
HCO_3	313	0.46
Total	36 674	100.00

TEST CYLINDERS DESCRIBED

Two by four-inch cylinders have been used for a number of reasons among which is the 2-in. diameter roughly approximating the thickness of the wall of many of the tile used in the public ditches of the Middle West. Special attention is, however, directed to the fact that these cylinders, while small, have been for the most part made of concrete, not mortar, although in none has there been used aggregate coarser than $\frac{3}{8}$ in. The aggregate passed all standard physical tests and was separated into screen sizes and recombined to produce a fineness modulus of 4.67. The cylinders were made in batches of nine, mix 1:3, water-cement ratio 0.59 to 0.64 and in all but a few special cases were cured the first 24 hours in the moist closet at room temperatures. More than 12,000 cylinders form the basis of these studies of curing with many long-time tests of 1, 3 and 5 years.

RESISTANCE TO SULFATE WATERS OF CONCRETE CURED IN WATER VAPOR OF VARIOUS HIGH TEMPERATURES

From experiments that began July 10, 1922, it was learned[1] that concrete cured in steam over boiling water displayed in the laboratory remarkable resistance to solutions of magnesium sulfate ($Mg\,SO_4$) and sodium sulfate ($Na_2\,SO_4$). Some of the cylinders of these earlier series are still under observation and their conditions, as indicated by length changes, are shown graphically in Fig. 1. For proper appreciation of the significance of these graphs it need only be said here that for the type of specimen used, a total length increase of 0.01 in. is indicative of 50 to 70 per cent loss of strength.[2] Note that resistance

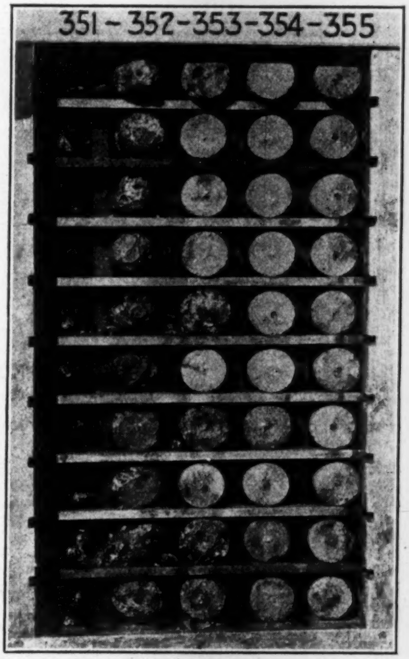

FIG. 2.—Cylinders From Series 351 to 355 Cured in Water Vapor for 12 Hours, after 24 Hours in Moist Closet, and Exposed Five Years to the Sulfate Water of Medicine Lake. S. Dak.

Series 351 cured at 190° F.
Series 352 cured at 212° F.
Series 353 cured at 235° F.
Series 354 cured at 260° F.
Series 355 cured at 285° F.

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[1] Dalton G. Miller, "Curing Conditions of Concrete Drain Tile a Factor of Resistance to Sulfate Waters," *Concrete*, June, 1924, p. 235.

[2] Dalton G. Miller, "Volume Change a Measure of Alkali Action," *Public Roads*, Vol. 5, No. 4, p. 12 (1924)

TABLE II.—DESCRIPTION AND TESTS OF CONCRETE CYLINDERS CURED IN WATER VAPOR BETWEEN TEMPERATURES OF 100 AND 350° F. AND EXPOSED TO THE ACTION OF SULFATE WATER OF MEDICINE LAKE, S. DAK., AND PARALLEL TESTS OF CHECK CYLINDERS STORED IN LABORATORY TANK.

Unless otherwise noted, the fineness modulus of aggregate is 4.67 and the mix is 1:3.
Each test result, with a few exceptions, is an average of 5 cylinders made on different days.
Figures in parentheses, in compression test columns, indicate percentage of normal strength based on parallel tests of cylinders from the same batches, stored in tap water in the laboratory.

Series	Cement, Laboratory Number	Cement	Water-Cement Ratio	Curing Method					Absorption at 21 days, per cent	Average Compressive Strength, lb. per sq. in.						
										Tank Specimens				Lake Specimens		
				Time in Moist Closet, hours	Time in Water, days	Time in Water Vapor, hours	Temperature of Water Vapor, deg. Fahr.	Time in Air, days		7 days	28 days	1 year	5 years	1 year	3 years	5 years
No. 87	11	$\frac{1}{2}$ A, $\frac{1}{2}$ B	0.59	3	..	69	100	25	6.6	3730	4120	5110	5470	1430 (28)	0	0
No. 88	11	“	0.59	6	..	66	100	25	6.7	3590	4320	4960	5450	1370 (28)	0	0
No. 89	11	“	0.59	12	..	60	100	25	6.7	4050	4680	5270	5200	1290 (25)	0	0
No. 90	11	“	0.59	24	..	48	100	25	6.7	4080	4220	5240	6270	1630 (31)	0	0
No. 91	11	“	0.59	48	..	24	100	25	6.8	3510	4060	5010	4970	1920 (38)	0	0
No. 92	11	“	0.59	24	27	..	...	28	6.7	2620	4540	5690	5400	3780 (66)	0	0
No. 93	11	“	0.59	72	..	..	...	25	7.0	3380	3560	5120	5140	3150 (62)	0	0
No. 94	11	“	0.59	24	..	48	100	24	6.8	3810	4000	5640	5910	2020 (36)	0	0
No. 313	65	M	0.60	24	20	..	...	35	5.9	3150	3950	6050	5680	2250 (37)	0	0
No. 315	65	M	0.60	24	..	48	100	53	6.2	3740	3800	5970	6320	4230 (71)	3390	3300 (53)
No. 114[a]	17	$\frac{1}{2}$ A, $\frac{1}{2}$ B	0.64	24	..	48	100	25	10.1	2270	2790	3040	3050	630 (21)	0	0
No. 82	11	$\frac{1}{2}$ A, $\frac{1}{2}$ B	0.59	3	.	69	155	25	6.9	3360	4210	5380	5550	500 (9)	0	0
No. 83	11	“	0.59	6	.	66	155	25	6.9	3840	4720	5700	5620	490 (9)	0	0
No. 84	11	“	0.59	12	..	60	155	25	6.7	4440	4960	5250	5920	1030 (20)	0	0
No. 85	11	“	0.59	24	..	48	155	25	6.6	4350	4550	6460	5830	1220 (19)	0	0
No. 86	11	“	0.59	48	..	24	155	25	6.7	3540	4210	6250	6320	1660 (27)	0	0
No. 92	11	“	0.59	24	27	..	...	28	6.7	2620	4540	5690	5400	3780 (66)	0	0
No. 93	11	“	0.59	72	..	..	...	25	7.0	3380	3560	5120	5140	3150 (62)	0	0
No. 95	11	“	0.59	24	..	48	155	25	6.4	4240	4370	5510	5510	1660 (30)	0	0
No. 97	11, 8	“	0.59	24	..	48	155	25	6.3	3900	4770	5690	5970	1880 (33)	0	0
No. 99	11, 8	“	0.59	24	..	72	155	24	6.4	4490	4830	5410	5990	1530 (28)	0	0
No. 102	17	“	0.59	24	..	48	155	25	6.2	4550	4730	5580	5960	980 (18)	0	0
No. 104	17	“	0.59	24	..	72	155	24	6.1	4910	5180	5180	5630	1270 (25)	0	0
No. 174	18	“	0.59	24	..	48	155	35	6.1	4020	4390	4330	5650	3910 (90)	....	2740 (48)
No. 179	18	“	0.59	24	..	48	155	35	5.8	4110	4510	5210	6460	3820 (73)	....	1750 (27)
No. 184	18	“	0.59	24	..	48	155	35	6.0	4070	4530	5100	6110	4240 (83)	....	800 (13)
No. 314	65	M	0.60	24	..	48	155	53	6.0	4460	4010	6170	6810	5430 (88)	3920	3690 (54)
No. 107[a]	17	$\frac{1}{2}$ A, $\frac{1}{2}$ B	0.64	24	..	48	155	25	9.8	2660	3080	3580	3580	770 (23)	0	0
No. 109[a]	17	“	0.64	24	..	72	155	24	9.6	2670	3220	3490	3580	930 (27)	0	0
No. 112[a]	17	“	0.64	24	27	..	...	..	10.0	1650	2630	3540	2790	1790 (51)	0	0
No. 113[a]	17	“	0.64	72	..	..	...	25	10.7	2000	2000	2980	2940	840 (28)	0	0
No. 115[a]	17	“	0.64	24	..	48	155	25	10.1	2730	2900	3400	3020	860 (25)	0	0
No. 127[a]	17	“	0.64	24	..	48	155	53	9.1	2530	2710	3460	3290	2280 (66)	....	0
No. 129[a]	17	“	0.64	24	..	72	155	52	9.0	2700	3120	3320	3230	1970 (59)	....	0
No. 351	74	“	0.62	24	..	12	190	54	6.6	2650	2940	5320	6870	1730 (33)	0	0
No. 391	74	”	0.62	24	20	..	...	35	6.3	3130	4890	6060	....	2480 (41)	0	0
No. 77	11	$\frac{1}{2}$ A, $\frac{1}{2}$ B	0.59	3	..	69	212	25	7.9	1110	1250	1250	2810	1210 (97)	1340	2630 (94)
No. 78	11	“	0.59	6	..	66	212	25	7.2	2260	3040	3130	5900	2840 (91)	2930	4120 (70)
No. 79	11	“	0.59	12	..	60	212	25	6.9	3400	4120	4550	6020	4410 (97)	4940	5400(90)
No. 80	11	“	0.59	24	..	48	212	25	6.9	3060	4020	4600	5790	4330 (94)	4860	5150(89)
No. 81	11	“	0.59	48	..	24	212	25	6.7	2910	3850	4630	6730	4410 (95)	5340	6000(89)
No. 92	11	“	0.59	24	27	..	...	28	6.7	2620	4540	5690	5400	3780 (66)	0	0
No. 96	11	“	0.59	24	..	48	212	25	6.5	3770	4410	4560	5720	4300 (94)	....	4930(86)
No. 98	11, 8	“	0.59	24	..	24 24	155 212	25	6.7	4180	4120	5020	6190	4340 (87)	....	5310 (86)
No. 100	11, 8	“	0.59	24	..	48 24	155 212	24	6.2	4310	4960	5730	5750	5540 (97)	....	5890 (102)
No. 101	11, 8	“	0 59	24	..	24 48	155 212	24	6.3	4110	4710	4890	6490	4640 (95)	....	5330 (82)
No. 103	17	“	0.59	24	..	24 24	155 212	25	6.0	4600	5510	5290	6280	4980 (94)	5510	4910 (78)
No. 105	17	“	0 59	24	..	48 24	155 212	24	6.0	4820	5070	4910	6720	5220 (106)	6000	5680 (85)

[a] Standard Ottawa Sand Cylinders.

TABLE II.—*Continued.*

Series	Cement, Laboratory Number	Cement	Water-Cement Ratio	Curing Method					Absorption at 21 days, per cent	Average Compressive Strength, lb. per sq. in.						
										Tank Specimens				Lake Specimens		
				Time in Moist Closet, hours	Time in Water, days	Time in Water Vapor, hours	Temperature of Water Vapor, deg. Fahr.	Time in Air, days		7 days	28 days	1 year	5 years	1 year	3 years	5 years
No. 106.....	17	½ A, ½ B	0.59	24	..	24 48	155 212	24	5.7	5110	5900	5320	6020	5250 (99)	5830	5720 (95)
No. 296.....	61	"	0.62	24	..	48	212	53	6.5	3330	3660	5020	5760	4390 (88)	5840	5950 (103)
No. 297.....	63	A	0.60	24	..	48	212	53	6.4	3650	3660	4680	6020	4600 (98)	4960	5480 (91)
No. 298....	62	B	0.62	24	..	48	212	53	6.9	3700	3830	4580	6440	4480 (98)	4840	5600 (87)
No. 299.....	33	D	0.60	24	..	48	212	53	6.4	3690	3770	4620	6330	4270 (92)	4910	5900 (93)
No. 300.....	34	C	0.67	24	..	48	212	53	6.6	3880	4540	4940	6110	4890 (99)	5690	5810 (95)
No. 301.....	61	½ A, ½ B	0.62	24	..	48	212	53	6.5	3690	3610	4500	4840	4480 (100)	5160	5300 (110)
No. 302.....	35	E	0.60	24	..	48	212	53	6.2	3540	3530	4550	5040	4450 (98)	4660	4640 (92)
No. 303.....	37	F	0.60	24	..	48	212	53	6.0	3550	3900	5060	4890	4920 (97)	5920	5470 (112)
No. 304.....	39	G	0.60	24	..	48	212	53	6.2	3740	3920	4990	5870	4680 (94)	5060	5060 (86)
No. 305.....	41	H	0.60	24	..	48	212	53	6.1	3730	3840	4860	5380	4410 (91)	4340	5100 (95)
No. 306.....	61	½ A, ½ B	0.62	24	..	48	212	53	6.2	3280	3920	4480	6570	4410 (98)	5990	5230 (80)
No. 307.....	40	I	0.60	24	..	48	212	53	5.9	3420	4150	5090	5850	4190 (82)	4990	4530 (77)
No. 308.....	42	J	0.62	24	..	48	212	53	6.4	2650	3240	4680	5310	3480 (74)	4440	4580 (86)
No. 309.....	55	K 1	0.62	24	..	48	212	53	6.5	3260	4200	4950	5800	4910 (99)	4910	4690 (86)
No. 310.....	60	L	0.60	24	..	48	212	53	6.2	3260	3870	5060	6380	4460 (88)	4720	5770 (90)
No. 311.....	65	M	0.60	24	..	48	212	53	5.5	4660	5580	5810	6740	5570 (96)	5420	5960 (88)
No. 313.....	65	M	0.60	24	20	..	...	35	5.9	3150	3950	6050	5680	2250 (37)	0	0
No. 352.....	74	½ A, ½ B	0.62	24	..	12	212	54	6.9	2450	2910	5230	6070	4240 (81)	3850	0
No. 391.....	74	"	0.62	24	20	..	...	35	6.3	3130	4890	6060	....	2480 (41)	0	0
No. 584.....	139	"	0.62	24	20	*b*	212	35	6.3	3740	5150	5790	....	3350 (58)	0	0
No. 585.....	139	"	0.62	24	..	*b*	212	55	6.4	2770	2860	5430	....	5370(99)	0	0
No. 586–587	139	"	0.62	24	..	*b*	212	54	6.6	2970	2920	5800	....	4400 (76)	0	0
No. 635–636	139	"	0.64	24	..	48	212	53	6.3	3960	4330	4250	....	4370 (103)	5950	....
No. 640.....	139	"	0.64	24	20	..	...	35	6.5	3320	4470	5800	....	4530 (78)	0	0
No. 641.....	139	"	0.64	24	..	48	212	53	6.9	3590	3760	4530	....	3740 (83)	5360	....
No. 108[a]....	17	"	0.64	24	..	24 24	155 212	25	9.8	2590	2910	2930	2880	2540 (87)	3390	2580 (90)
No. 110[a]....	17	"	0.64	24	..	48 24	155 212	24	9.5	2600	3160	2940	2590	2720 (93)	3160	2360 (91)
No. 111[a]....	17	"	0.64	24	..	24 48	155 212	24	9.7	2510	3130	2630	3020	2450 (93)	2820	2320 (77)
No. 112[a]....	17	"	0.64	24	27	..	...	..	10.0	1650	2630	3540	2790	1790 (51)	0	0
No. 113[a]....	17	"	0.64	72	..	..	...	25	10.7	2000	2000	2980	2940	840 (28)	0	0
No. 116[a]....	17	"	0.64	24	..	48	212	25	10.3	2220	2470	2500	3250	2430 (97)	....	2460 (73)
No. 128[a]....	17	"	0.64	24	..	24 24	155 212	53	9.1	2350	2480	2830	3340	3180 (112)	....	2040 (61)
No. 130[a]....	17	"	0.64	24	..	48 24	155 212	52	9.1	2750	2720	2830	3130	3080 (109)	....	1740 (56)
No. 131[a]....	17	"	0.64	24	..	24 48	155 212	..	9.2	2630	2470	2600	2940	2560 (98)	....	1730(59)
No. 353.....	74	"	0.62	24	..	12	235	54	7.3	1900	2750	4780	5410	3800 (79)	3970	2480 (46)
No. 391.....	74	"	0.62	24	20	..	...	35	6.3	3130	4890	6060	....	2480 (41)	0	0
No. 354.....	74	"	0.62	24	..	12	260	54	7.1	2270	2490	4880	5570	3760 (77)	4160	3320 (69)
No. 391.....	74	"	0.62	24	20	..	...	35	6.3	3130	4890	6060	....	2480 (41)	0	0
No. 355.....	74	"	0.62	24	..	12	285	54	7.2	2260	2870	4340	5250	3870 (89)	3970	4190 (80)
No. 391.....	74	"	0.62	24	20	..	...	35	6.3	3130	4890	6060	....	2480 (41)	0	0
No. 430.....	97–98	K 1	0.64	24	..	12	285	54	6.6	2960	3470	3950	....	3680 (93)	5000	....
No. 431.....	86–99	I	0.64	24	..	12	285	54	6.1	3650	4150	4470	....	4290 (96)	5440	....
No. 432.....	82–95	C	0.67	24	..	12	285	54	6.9	3330	3820	5530	....	4930 (89)	5460	....
No. 433.....	83	H	0.64	24	..	12	285	54	6.5	3460	3950	5110	....	4840 (95)	5510	....

[a] Standard Ottawa Sand Cylinders.

[b] One minute.

TABLE III.—STRENGTH AND ABSORPTION OF CONCRETE CURED IN WATER VAPOR BETWEEN TEMPERATURES OF 100 AND 350° F. AS INFLUENCED BY DURATION OF CURING PERIOD.

All cylinders were first cured 24 hours in moist closet at room temperatures and following curing in water vapor were stored in dry air until tested.

Each test result is average for 4 or more cylinders. Cement used was equal parts brands A and B.

Check Cylinders Cured in Water			Temperature of Water Vapor, deg. Fahr.	Cylinders Cured in Water Vapor ¾ to 6 hours											
				¾ hour			1½ hours			3 hours			6 hours		
Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.			Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.	
	7 days	28 days			7 days	28 days		7 days	28 days		7 days	28 days		7 days	28 days
	3270		100		2630			2460			3080			3290	
	3550		155		2940			3240			3380			3730	
5.9	3230	4720	212	6.9	3020	2880	7.4	2590	2400	7.2	2890	3130	7.0	3220	3470
5.6	3730	5100	230	7.0	2060	2170	6.9	1830	2190	6.7	2180	2320	6.6	2390	2990
5.8	3640	4960	260	7.4	1960	1930	7.1	2000	2130	7.2	2170	2460	7.0	2790	2870
5.8	3790	5780	285	7.3	1780	1740	7.2	2010	2220	7.3	2420	2590	6.8	3080	3370
5.8	3810	5050	315	6.9	2010	2020	6.8	2490	2640	6.5	3090	3030	6.8	3560	3900
5.7	3840	5310	350	7.3	1670	1940	7.0	2500	2800	6.7	3210	3310	6.8	3110	3540
5.8	3670	5150	Average 212–350° F.	7.1	2080	2110	7.1	2240	2400	6.9	2660	2810	6.8	3030	3360

Temperature of Water Vapor, deg. Fahr.	Cylinders Cured in Water Vapor 12 hours to 8 days														
	12 hours			24 hours			2 days			4 days			8 days		
	Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.	
		7 days	28 days		7 days	28 days		7 days	28 days		7 days	28 days		7 days	28 days
100		3470			4280			4220			4870			5280	
155		4020			4420			4460			4720			4820	
212	7.1	3570	3580	7.2	3960	4190	6.6	4260	4670	6.1	4330	4990	6.1	5180	6050
230	6.8	2640	3200	6.6	3560	3250	6.9	3900	4650	6.1	4480	4600	6.2	3830	4450
260	6.7	3190	3380	6.7	3480	3810	6.6	3720	3880	6.4	3820	3810	6.6	3260	3690
285	6.5	3320	3420	6.3	3740	4160	6.7	3300	3600	6.5	3740	4230	6.5	3540	4300
315	6.5	3410	3780	6.8	3180	3750	6.8	3440	3970	6.6	3430	4280	6.8	3580	4640
350	6.7	3280	3470	6.8	3830	3840	6.5	3530	4710	6.3	4140	4320	6.2	3770	4260
Average 212–350° F.	6.7	3340	3470	6.7	3630	3830	6.7	3710	4250	6.3	3990	4370	6.4	3860	4570

Temperature of Water Vapor, deg. Fahr.	Cylinders Cured in Water Vapor 12 to 32 days and Tested Dry at All Time Periods 4 hours After Completion of Curing										
	12 days	14 days	16 days	18 days	20 days	22 days	24 days	26 days	28 days	30 days	32 days
	Compressive Strength, lb. per sq. in										
100	4760	4910	4610	4760	4460	4290	5380	4950	5100	4610	4530
155	5190	4690	5210	4590	4740	4850	5000	4730	5020	4960	4550
212	4670	4550	5080	4580	4530	4840	4430	4600	4290	4500	4860
Average 100–212° F.	4870	4720	4970	4640	4580	4660	4940	4760	4800	4690	4650

of these cylinders has in each group been in the same order as the duration of time in air for the water-cured cylinders and of time in steam for the steam-cured ones.

Following the earlier laboratory work, many cylinders were made and exposed to the action of the natural alkaline waters of Medicine Lake, S. Dak., 18 miles northwest of Watertown. An average of four analyses of water samples taken December 10, 1923, February 14, 1924, April 29, 1924, and July 1, 1925, are given in Table I.

In Table II are to be found tests of the Medicine Lake cylinders compared with tests of check cylinders stored in tap water in the laboratory. Space does not permit detailed discussion of the data of Table II, but note in particular that of the 36 series in which curing at 212° F. was introduced for 12 hours and longer and for which 1 and 5-year tests are available, the strength ratios average respectively 95 and 84 per cent; averaging the results of tests of cylinders from 19 series cured at 155° F., the strength ratios are 40 and 7 per cent respectively at 1 and 5 years; averaging likewise the strength ratios of 8 series of cylinders cured at 100° F., the 1 and 5-year tests are respectively 35 and 7 per cent. Tests of cylinders steam-cured at temperatures above 212° F. are complete in too few series to justify exact comparison with the 100, 155 and 212° F. groups but the photograph of Fig. 2 shows conditions at 5 years of cylinders of series 351 to 355 cured 12 hours at temperatures of 190, 212, 235, 260 and 285° F. It is clear from a study of Fig. 2 and the data of Table II that for the 12-hour curing period, the cylinders are without question failing in the order of curing temperatures between 190 and 285° F. It is not possible at this time to state definitely the most effective curing conditions with respect to temperatures and duration, but later tests of cylinders now in Medicine Lake should give much definite information on this subject for temperatures of 100 to 350° F. and curing periods up to 8 days.

ABSORPTION OF CONCRETE CURED IN HIGH-TEMPERATURE WATER VAPOR IS NOT A CRITERION OF RESISTANCE TO SULFATE ACTION

Referring to the absorption results of Table III, it is curious to find that the cylinders cured continuously in water averaged from 0.5 to 1.3 per cent lower in absorption than did the cylinders cured in water vapor at the different temperatures although the tendency is very evident for the absorption to decrease as the duration of the curing period increases for the cylinders cured in water vapor. For identical curing periods the absorption was nearly constant regardless of temperature.

TABLE IV.—STRENGTH OF CONCRETE CURED IN WATER VAPOR BETWEEN THE TEMPERATURES OF 100 AND 350° F. AS INFLUENCED BY THE DURATION OF CURING PERIOD AND THE CEMENT.

All cylinders were first cured 24 hours at room temperatures in moist closet.
Cylinders cured in water vapor were stored in air and tested dry in compression at 7 days.
Test results are in all cases the average for 4 or more cylinders.
Figures in boldface type indicate retrogression of strength for that test.

Cement		Check Cylinders Cured in Water			Compressive Strength at 7 days, lb. per sq. in.									
		Absorption, per cent, 21 days	Compressive Strength, lb. per sq. in.		Cylinders Cured in Water Vapor at 100° F.					Cylinders Cured in Water Vapor at 155° F.				
Number	Brand		7 days	28 days	1½ hours	6 hours	24 hours	96 hours	Average	1½ hours	6 hours	24 hours	96 hours	Average
FRESH CEMENTS														
274.....	I	5.9	4240	5500	3360	3970	4390	5810	4380	4200	4560	**4090**	5480	4580
275.....	K1	5.8	4010	6340	3550	3770	4730	**4540**	4150	3920	**3700**	4610	**4460**	4170
276.....	H	6.1	3680	5210	3110	3450	3930	4610	3780	3710	4490	4770	5690	4670
277.....	C	6.2	3640	5620	2610	3190	3800	4170	3440	3020	3710	4490	5350	4140
278.....	E	5.9	3560	5700	2900	2900	3670	4110	3400	3240	3930	4790	5550	4380
279.....	F	5.5	5110	6700	3750	4090	5370	**5040**	4560	4330	5370	**5200**	5850	5190
280.....	G	6.2	4240	5270	2980	3800	4260	4280	3830	3550	4160	5130	5740	4650
281.....	M	5.8	4040	5270	3310	3810	4280	4680	4020	3480	4610	**4410**	5660	4540
282.....	P	5.5	4420	6590	3510	3830	4730	**4470**	4140	3570	4820	**4530**	5650	4640
234.....	D	5.5	4470	6050	3670	4150	4990	6090	4730	3860	4960	6070	6420	5330
Average	.....	5.8	4140	5830	3280	3700	4420	4780	4040	3690	4430	4810	5590	4630
CEMENTS STORED FOR ONE YEAR														
206.....	I	6.1	2560	5200	600	2370	**2130**	3480	2140	....	....	....	....	....
207.....	K1	6.5	2560	4510	980	1870	2260	2820	1980	1220	1800	2310	3700	2260
208.....	H	6.5	2910	4620	1940	2010	3150	**3000**	2520	1940	2140	2990	3770	2710
209.....	C	6.8	2140	4520	830	1310	2280	**2140**	1640	....	....	....	....	....
210.....	E	6.3	3430	4890	1970	2980	3420	3900	3070	2500	3090	3600	4160	3340
211.....	F	6.2	3590	4900	2450	**2420**	3840	3890	3150	2130	2470	3080	4870	3140
212.....	G	6.3	2930	4740	1870	2260	3250	3560	2730	....	....	....	....	....
213.....	M	6.6	2760	4510	2120	**2080**	3210	3430	2710	2310	2530	3120	4120	3020
215.....	P	6.1	3860	4670	2880	2990	4160	**3730**	3440	....	....	....	....	....
217.....	D	6.3	3360	5220	1690	2290	3180	3880	2760	1850	2230	3520	4230	2960
Average	.....	6.4	3010	4780	1730	2260	3090	3380	2610	1990[a]	2380[a]	3100[a]	4140[a]	2900[a]

[a] Averages for 6 cements only.

Cement		Compressive Strength at 7 days, lb. per sq. in.									
		Cylinders Cured in Steam at 212° F.					Cylinders Cured in Steam at 260° F.				
Number	Brand	1½ hours	6 hours	24 hours	96 hours	Average	1½ hours	6 hours	24 hours	96 hours	Average
FRESH CEMENTS											
274......	I	3780	3790	4410	4740	4180	3160	3630	4010	**3630**	3610
275......	K1	3310	3410	4440	**4100**	3820	2710	3040	4550	**3830**	3530
276......	H	2520	3080	3160	4290	3260	2450	2820	3440	3780	3120
277......	C	2580	3050	3940	5190	3690	2260	2680	4240	4760	3490
278......	E	2740	**2680**	4230	4590	3560	2390	2970	4090	4440	3470
279......	F	3790	4050	**4020**	5130	4250	3470	4120	5310	**4330**	4310
280......	G	2840	3510	3950	4370	3670	2760	2920	4260	**2050**	3000
281......	M	3170	**3000**	4430	4680	3820	2340	2840	3770	5240	3550
282......	P	3770	3860	4180	5620	4360	3040	3940	5330	**4750**	4270
284......	D	3800	4000	4610	5530	4490	3180	4120	4890	**3660**	3960
Average..	....	3230	3440	4140	4820	3910	2780	3310	4390	**4050**	3630

TABLE IV.—*Continued.*

Cement		Compressive Strength at 7 days, lb. per sq. in.									
		Cylinders Cured in Steam at 212° F					Cylinders Cured in Steam at 260° F.				
Number	Brand	1½ hours	6 hours	24 hours	96 hours	Average	1½ hours	6 hours	24 hours	96 hours	Average
CEMENTS STORED FOR ONE YEAR											
206......	I	1530	**1470**	2290	2850	2030	1180	1370	2570	2930	2010
207......	K1	2120	**1520**	2320	3420	2340	1290	2100	2910	4040	2580
208......	H	1700	1950	2560	4360	2640	1520	2260	3300	4070	2790
209......	C	1200	1610	2100	3930	2210	1230	2130	3220	3800	2590
210......	E	1860	2090	2760	4380	2770	1340	2250	3770	4900	3060
211......	F	2070	2520	3340	4610	3130	1950	2610	3660	5540	3440
212......	G	1600	2200	2870	3780	2610	1930	2510	3730	**2950**	2780
213......	M	1580	1980	2480	4590	2660	1260	2120	3350	4610	2830
215......	P	2270	2850	3750	4830	3420	2470	2980	4250	5070	3690
217......	D	2120	2690	2920	3650	2840	1520	2080	3100	**3040**	2410
Average..	....	1800	2090	2740	4030	2660	1570	2240	3390	4090	2820

Cement		Compressive Strength at 7 days, lb. per sq. in.									
		Cylinders Cured in Steam at 315° F.					Cylinders Cured in Steam at 350° F.				
Number	Brand	1½ hours	6 hours	24 hours	96 hours	Average	1½ hours	6 hours	24 hours	96 hours	Average
FRESH CEMENTS											
274......	I	2970	4070	**3240**	3460	3440	3150	3520	4610	4610	3970
275......	K1	2860	3840	**3300**	3590	3400	2910	3600	3780	4720	3750
276......	H	2290	3430	4270	**3710**	3430	2060	4320	4570	**4180**	3780
277......	C	2220	3590	3960	**3860**	3410	2200	3880	4340	4860	3820
278......	E	2160	4030	4950	**4910**	4010	2100	4460	5330	**4410**	4080
279......	F	3320	4230	**4100**	4430	4020	3200	4230	4850	6230	4630
280......	G	2710	**2400**	2820	3750	2920	2660	2970	4110	4850	3650
281......	M	2650	3760	4470	**4070**	3740	2870	4180	4490	5170	4180
282......	P	3050	4170	4540	4900	4170	3020	4040	4930	5630	4410
284......	D	3250	4190	**3010**	**2780**	3310	3110	3310	4330	4520	3820
Average..	....	2750	3770	3870	3950	3590	2730	3850	4530	4920	4010
CEMENTS STORED FOR ONE YEAR											
206......	I	830	1990	3080	**2960**	2210	1250	2540	3020	4200	2750
207......	K1	1140	2480	3940	**3760**	2830	1450	2910	4110	4320	3200
208......	H	1710	2650	4810	**4560**	3430	1730	2850	4790	**3940**	3330
209......	C	1160	2390	3860	4050	2860	1460	2520	3760	3800	2880
210......	E	1610	2910	4120	4980	3400	1440	2860	4880	**4090**	3320
211......	F	1830	3470	5450	**5320**	4020	1340	3470	5090	**4360**	3560
212......	G	1700	2990	3620	4310	3150	2070	2820	4050	5340	3570
213......	M	1750	2730	4870	**4510**	3460	1480	2810	4390	4530	3300
215......	P	1600	3360	**3080**	4990	3260	2680	3340	4710	4710	3860
17......	D	1980	2420	4170	**2700**	2820	2040	2600	3370	4260	3070
Average..	....	1530	2740	4100	4210	3140	1690	2870	4220	4350	3280

All absorption results are based on the standard A.S.T.M. absorption test for drain tile[1] that provides for oven drying at a temperature of not less than 230° F. followed by 5 hours boiling.

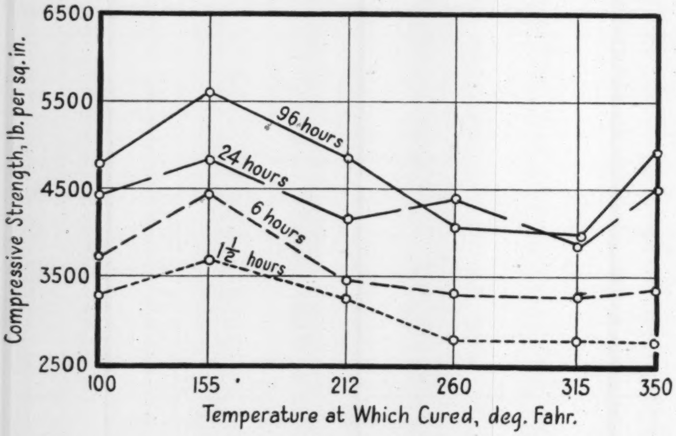

FIG. 3.—7-Day Strength of Concrete, Made of Fresh Cements, as Influenced by Curing in Water Vapor at Temperatures of 100 and 350° F. for Time Periods of 1½ to 96 Hours, Based on Data of Table IV.

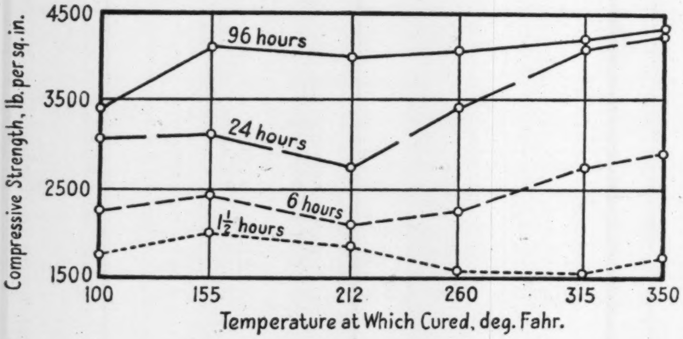

FIG. 4.—7-day Strength of Concrete Made of Cements After Storage for One Year, as Influenced by Curing in Water Vapor at Temperatures Between 100 and 350° F. for a Period of 1½ to 96 Hours, Based on Data of Table IV.

STRENGTH OF CONCRETE CURED IN WATER VAPOR OF VARIOUS HIGH TEMPERATURES

Study of the data of Tables III and IV, based on tests of 4140 cylinders, brings out a number of facts of unusual interest not generally known in connection with the strength of concrete cured in water vapor at higher temperatures.

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[1] Standard Specifications for Drain Tile (C 4 – 24), 1927 Book of A.S.T.M. Standards, Part II, p. 190.

Nothing in the data of either Tables III or IV indicates a consistent increase of strength, for the fresh cements, for increase of temperature above 100° F. with the single exception of those cylinders cured at 155° F. On the other hand those cylinders of Table IV made with the cements that had been stored for one year showed a general tendency to increase in strength as the curing temperature was increased. See Figs. 3 and 4.

TABLE V.—PHYSICAL TESTS OF CEMENTS USED IN CYLINDERS UPON WHICH TABLE IV IS BASED.

Cement	Fineness Test			Normal Consistency, per cent	Time of Setting								Tensile Strength, lb. per sq. in.		
					Vicat Needle				Gillmore Needle						
	Retained on No. 200 Sieve, per cent	Retained on No. 250 Sieve, per cent	Retained on No. 300 Sieve, per cent		Initial		Final		Initial		Final		3 days	7 days	28 days
					hr.	min.	hr.	min.	hr.	min.	hr.	min.			
FRESH CEMENTS															
I	10.36	1.70	6.28	24.00	2	15	5	55	3	15	5	55	246	317	427
K1	7.26	1.62	6.86	25.25	2	35	5	15	3	40	6	30	243	317	386
H	13.62	2.25	6.82	24.25	2	35	6	20	3	50	6	55	218	282	335
C	9.91	1.77	6.06	26.25	3	05	6	25	3	55	6	45	220	258	356
E	8.88	2.10	9.97	24.25	2	55	5	45	3	40	6	35	219	310	395
F	8.98	2.24	9.42	25.25	3	20	5	35	4	20	6	05	242	303	364
G	11.16	1.58	6.84	25.00	4	35	6	50	5	20	7	05	232	295	368
M	10.58	1.81	6.69	25.00	4	10	6	40	5	10	7	10	243	312	393
P	7.97	1.47	9.95	25.00	3	30	6	00	4	15	6	45	251	356	451
D	11.31	1.62	6.95	24.75	3	20	5	35	3	50	6	50	236	352	386
STORED CEMENTS															
I	8.87	1.24	6.23	.....	..	..	..	..	..	..	..	..	...	...	...
K1	9.28	1.30	7.06	24.25	4	00	9	20	5	35	9	50	...	...	...
H	14.04	1.86	7.46	24.25	3	45	8	55	5	05	9	35	114	196	312
C	6.14	1.04	4.31	.....	..	..	..	..	..	..	..	..	...	...	...
E	7.44	1.48	5.46	24.50	4	20	7	35	4	50	8	30	166	258	367
F	8.57	1.72	6.61	25.25	2	15	7	55	4	10	8	25	145	265	390
G	11.09	1.80	6.11	.....	..	..	..	..	..	..	..	..	...	...	...
M	13.40	1.87	6.43	24.75	2	05	7	20	4	00	7	30	152	224	356
P	8.46	1.47	5.35	.....	..	..	..	..	..	..	..	..	...	...	...
D	11.86	1.71	6.54	24.75	4	05	9	10	4	35	9	20	145	230	348

NOTE.—All Cements O. K. Under Steam Pat Test.

The highest average compressive strength for those cylinders of Table IV in which the 12 fresh cements were used is the value of 5830 lb. per sq. in. for the 28-day water-cured cylinders, the nearest approach to this result being 5590 lb. per sq. in. for the cylinders cured 96 hours at 155° F. Figure 3 shows the trend of strength for the various curing conditions and temperatures and it is quite evident that the specimens cured at the temperature of 155° F. were consistently stronger for any curing period than were those cured at the other temperatures. Note also that the test results for the cylinders cured at temperatures of 260 and 315° F. were more erratic than were those for the cylinders cured at 350° F. and at temperatures of 212° F. and downward.

The highest average compressive strength for those cylinders of Table IV in which the 12 stored cements were used is the value of 4820 lb. per sq. in. for the cylinders cured 96 hours at 212° F., this result being but 50 lb. in excess of that of 4780 lb. per sq. in. for the 28-day water-cured cylinders.

Comparing the curves of Figs. 3 and 4, it is evident that the strength tests were more uniformly consistent, although lower, for the stored than for the fresh cements with the closest agreement of actual strengths for curing temperatures of 260, 315 and 350° F. for the 24 and 96-hour curing periods.

TABLE VI.—CHEMICAL ANALYSES OF CEMENTS AS USED IN CYLINDERS OF TABLE IV.

Chemical Analysis by the Division of Tests, Bureau of Public Roads, U. S. Department of Agriculture. All values are given in per cent.

Cement		Silica (SiO_2)	Iron (Fe_2O_3)	Alumina (Al_2O_3)	Lime (CaO)	Magnesia (MgO)	Sulfuric Anhydride (SO_3)	Loss on Ignition	Total
Number	Brand								
				FRESH CEMENTS					
274	I	22.15	3.30	5.80	63.55	2.00	1.65	1.65	100.10
275	Kl	21.40	3.06	5.74	62.50	3.84	1.85	1.55	99.94
276	H	21.50	3.46	6.24	63.30	1.77	1.89	1.50	99.66
277	C	22.25	3.54	4.81	62.35	4.53	1.49	1.10	100.07
278	E	21.45	3.79	6.01	62.25	3.77	1.34	1.10	99.71
279	F	20.80	3.63	6.57	63.80	1.74	1.73	1.60	99.87
280	G	21.80	3.63	5.42	63.45	1.47	2.12	2.05	99.94
281	M	21.55	2.57	6.98	62.20	2.57	1.54	2.50	99.91
282	P	22.05	3.54	6.31	64.15	1.61	1.66	0.85	100.17
284	D	21.55	2.50	5.80	63.75	4.29	1.61	0.75	100.25
Average		21.65	3.30	5.97	63.13	2.76	1.69	1.46	99.96
				STORED CEMENTS					
206	I	21.05	3.38	5.17	64.15	1.77	1.58	2.85	99.95
207	Kl	22.40	3.22	4.93	62.10	4.22	1.68	1.60	100.15
208	H	22.50	3.46	5.49	63.00	1.92	1.82	1.95	100.14
209	C	21.95	3.22	4.58	62.40	4.33	1.37	2.35	100.20
210	E	22.25	3.62	6.63	62.05	2.43	2.11	1.10	100.19
211	F	22.35	3.22	6.33	63.35	1.70	2.28	0.70	99.93
212	CT	21.85	3.38	5.87	65.10	1.20	1.37	1.50	100.27
213	M	22.55	2.81	6.79	62.80	2.53	1.90	1.00	100.38
215	P	20.70	3.14	6.96	64.50	1.41	1.54	1.55	99.80
217	D	21.50	3.02	5.63	64.00	2.95	1.61	1.20	99.91
Average		21.91	3.25	5.84	63.35	2.45	1.73	1.58	100.09

The results recorded in Tables III and IV are somewhat contrary to those reported a number of years ago[1] based on tests made in 1907 and 1908 in the Structural Materials Laboratory of the U. S. Geological Survey at St. Louis, Missouri, in which it was found:

> "A compressive strength considerably (in some cases over 100 per cent) in excess of that obtained normally after aging for six months, may be obtained in two days by using steam under pressure for curing the mortar or concrete."

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[1] R. J. Wig, "The Effect of High-pressure Steam on the Crushing Strength of Portland-Cement Mortar and Concrete," *Technologic Paper No. 5*, U. S. Bureau of Standards, 1911; also *Proceedings*, Am. Soc. Testing Mats., Vol. XI, p. 580 (1911).

No satisfactory explanation can be offered as to this disagreement although the thought is suggested that it may have been due to a difference of some kind in the cements used in the two experiments; possibly the result of age and conditions of storage.

The fresh cements referred to in Table IV were purchased in the open market from warehouse stock newly received, as indicated by invoices, while the stored cements were lots of the same brands that had been kept in their original bags in a finished room, winter heated, and were not lumpy when tested. Physical tests of the cements used in the cylinders of Table IV are to be found in Table V, while in Table VI are chemical analyses of cements from the plants, although not of the identical lots of cements.

Cylinders of all the cements, both fresh and stored, showed retrogression of strength for some time period in some of the temperatures, particularly for the 4-day periods at the temperatures of 260 and 315° F., followed by full recovery of strength in tests at other, and higher, temperatures. Similar results were noted in tests of steam-cured briquets by Thorvaldson and Vigfusson[1] of the University of Saskatchewan, as a result of an interesting series of experiments under the auspices of a research committee of the Engineering Institute of Canada, for which the explanation is offered that:

> "It seems probable that the first action, causing a loss in tensile strength, is due to a change in the tricalcium aluminate of the cement and that this change is the primary cause of the increase in the sulfate resistance of the mortar. The second change, causing an increase in tensile strength, would then probably be due to hydration of the silicates, speeded up by the action of steam or possibly partly due to the formation of stable cementing substances from the aluminate."

So far as known, these authors are the first to attempt an explanation of this pnenomenon although noted by others.[1, 2, 3, 4]

Concrete cured in water vapor between temperatures of 100 and 285° F. and stored in water continues to increase in strength at a rate not greatly different from that of check cylinders cured in water at room temperatures although the rate of increase is perhaps somewhat retarded depending on the temperature at which cured and the duration of the curing period. This statement is based on a study of the 7 and 28-day and the 1 and 5-year tests of the tank specimens recorded in Table II. Data are not available for temperatures above 285° F.

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[1] Thorvaldson and Vigfusson, "The Effect of Steam Treatment of Portland Cement Mortars on Their Resistance to Sulfate Action," *The Engineering Journal*, Vol. XI, No. 3, p. 174 (1928).

[2] C. C. Wiley, "Effect of Temperature on the Strength of Concrete," *Engineering News-Record*, Vol. 102, No. 5, p. 179 (1929).

[3] Edward E. Bauer, "High Early Strength Concrete," *Proceedings*, Am. Concrete Inst., Vol. XXV, p. 314, (1929).

[4] P. M. Woodworth, "Some Tests of Concrete Masonry Units Cured with High Pressure Steam," *Journal*, Am. Concrete Inst., February, 1930, p. 504.

The influence on the 28-day strength of concrete of applying water vapor, of temperatures of 100, 155 and 212° F., at early ages is illustrated in Fig. 5. These graphs indicate that the curing of concrete under these conditions and temperatures should preferably be commenced 12 to 24 hours after making. Figure 5 is based on tests of cylinders made November 1923, entirely unrelated to the tests of Tables III and IV, yet the cylinders cured at 155° F. were in all cases stronger than those cured at either 100 or 212° F.

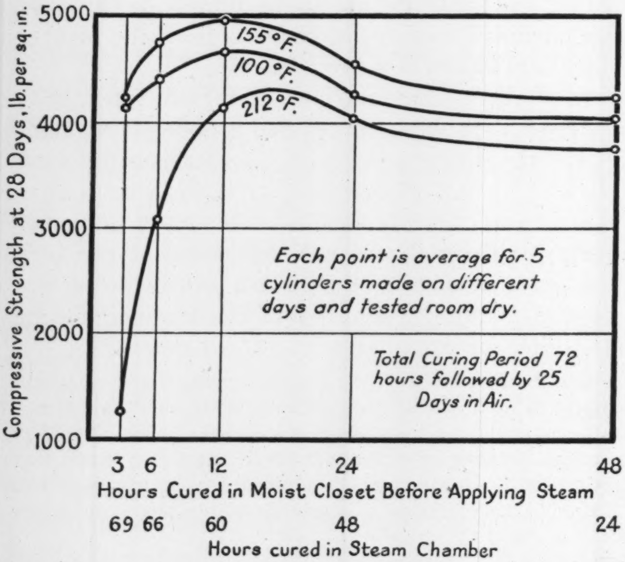


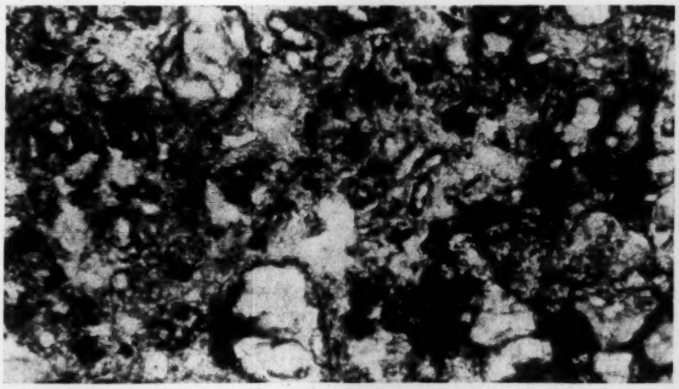
FIG. 5.—Influence on 28-day Strength of Concrete of Application at Early Ages of Water Vapor of Temperatures Indicated.

SOME PHYSICAL CHANGES OF CEMENT STEAM-CURED AT HIGH TEMPERATURES

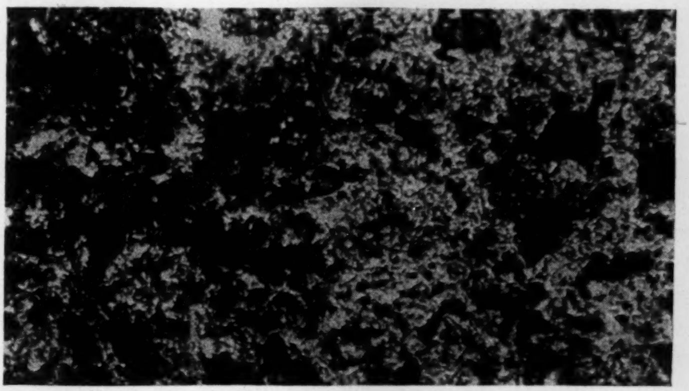
In Fig. 6 are shown photomicrographs of thin sections from two neat cement briquets. One of the briquets was cured 12 days in water at room temperatures while the other briquet was cured 24 hours in steam at 315° F. The same brand and lot of cement was used in the two briquets. It is very evident that many slightly altered unhydrated cement grains still remain in the water-cured briquet and equally evident that hydration of the steam-cured briquet has been much more complete, with all the cement grains greatly altered and reduced in size.

CRITICAL CURING TEMPERATURES OF CONCRETE FOR DEVELOPING STRENGTH AND RESISTANCE TO SULFATE WATERS

Solely from the standpoint of strength, little or nothing is gained by curing concrete in water vapor at a temperature much above 155° F. and little is gained, even at this temperature, by prolonging the curing period beyond 48 hours.



(*a*) Neat cement briquet cured 12 days in water at room temperatures.



(*b*) Neat cement briquet cured 24 hours in steam at 315° F.

FIG. 6.—Photomicrographs of Neat Cement Briquets Showing the Physical Effect of Different Curing Conditions (× 350).

Note how much more completely hydration has progressed in the steam-cured briquet.

Solely from the standpoint of resistance to sulfate waters, nothing is gained by increasing the temperature of the water vapor in which concrete is cured until 212° F. is reached. Between 212 and 260° F., increased resistance follows increase of curing temperature. Data are yet incomplete for curing temperatures above 260° F. For a temperature of 212° F., concrete increases in resistance with increase of curing period up to 6 days. No data are yet available for longer curing periods and for other temperatures.

CONCLUSIONS

Based on tests of 2 by 4-in. concrete cylinders made of graded aggregate with fineness modulus of 4.67, mix 1:3, and water ratio 0.59 to 0.64, the effects on strength and resistance to sulfate waters of curing in water vapor at temperatures between 100 and 350° F. following 24 hours in moist closet at room temperatures of 68 to 75° F., when compared with tests of check specimens cured continuously in water at room temperatures, following 24 hours in moist closet, have been as follows:

1. Concrete after curing 12 to 24 hours in water vapor at temperatures between 100 and 350° F., followed by storage in dry air at room temperatures, has a compressive strength at 7 days not greatly different from that of 7-day concrete cured continuously in water at room temperatures.
2. Increase of length of time of curing beyond 48 hours has little influence on the compressive strength of concrete cured in water vapor at temperatures between 100 and 350° F. and concrete so cured ordinarily attains a maximum and fairly constant strength 80 to 90 per cent of that of 28-day concrete cured continuously in water at room temperatures.
3. Based on the 7 and 28-day and such 1 and 5-year tests as are now available, it appears that concrete cylinders stored in tap water following curing in water vapor between temperatures of 100 and 285° F. continue to increase in strength at a rate not essentially different from that of check cylinders cured in water at room temperatures.
4. For curing periods of equal lengths, variations in temperatures between the limits of 100 and 350° F. have no pronounced influence on the strength of concrete although the specimens made with fresh cements tested consistently stronger when cured at 155° F. than at the other temperatures while the specimens made of the cements that had been stored for one year and cured at 155° F. tested but 13 per cent weaker than those cured at the maximum temperature of 350° F. These statements are based on curing periods up to 8 days for temperatures between 100 and 350° F. and up to 32 days for temperatures of 100, 155 and 212° F.
5. For highest compressive strength of the concrete, the most favorable time for applying water vapor at temperatures of 100, 155 and 212° F. is apparently 12 to 24 hours after making. No data are available for the other temperatures.

6. The reaction of concrete made of portland cements from different mills to curing under these special conditions is essentially similar for both strength and resistance to sulfate waters.

7. Concrete made of all the cements used in the strength tests showed retrogression of strength for some time period while curing in water vapor at some temperatures between 100 and 350° F. Occurrence of this phenomenon was most frequent and generally of greatest magnitude in those groups of cylinders cured 96 hours at 260 and 315° F. with the result that the tests were more uniform at 100, 155, 212 and 350° F. than at either 260 or 315° F. This statement is based on results obtained with cylinders made of 12 brands of cements of which 10 were used separately and 2 in combination.

8. Concrete cylinders made of stored cements consistently tested lower in strength than did cylinders made of fresh cements for similar curing conditions although this difference was not great for temperatures above 212° F. and curing periods of 4 days.

9. With some exceptions, those cements that lost strength most rapidly in storage, as indicated by tests of cylinders following curing at all temperatures for the shorter time periods, were the ones that displayed greatest resistance to the action of sulfate waters.[1] This statement is made as indicative only of trend.

10. Curing in water vapor at temperatures between 100 and 190° F. did not generally increase resistance of concrete to the action of sulfate water; on the contrary, in some cases a decrease was indicated.

11. Curing concrete in water vapor at temperatures of 212° F. and upward markedly increased resistance to the action of sulfate waters with the data definitely indicating increase of resistance with increase of curing temperatures between 212 and 285° F. for a 12-hour curing period.

12. Curing concrete in water vapor at 212° F. has been more effective in developing resistance to the action of sulfate water when continued for 6 days than when continued but 2 days.

13. Data are not yet complete enough satisfactorily to correlate curing temperatures and lengths of curing periods with resistance to sulfate waters of concrete cured in water vapor for all temperatures between 100 and 350° F. although, within the limits of the experiments completed, it is significant that for temperatures between 100 and 285° F., those specimens cured at the highest temperatures and for the longest periods have made the most favorable showings.

14. Absorption of concrete cured in water vapor at high temperatures is not a criterion of resistance to sulfate waters.

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[1] Dalton G. Miller, "Resistance of Portland-Cement Concrete to the Action of Sulfate Waters as Influenced by the Cement," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 448 (1928).

FURTHER STUDIES ON THE WORKABILITY OF CONCRETE

By W. F. PURRINGTON[1] AND H. C. LORING[2]

SYNOPSIS

The paper describes an investigation of the determination of the workability of concrete by measuring the power consumed in mixing concrete.

The subject is approached from a laboratory and economic viewpoint. The former takes up the study of the power consumption of mixing concrete of 2000, 3000 and 4000 lb. per sq. in. design strength; the power consumption of concrete at varying consistencies and the variations in the relative workability of standard portland cements; the latter is an economic application of the vertical axis type of mixer to the rating of plastic cements.

INTRODUCTION

The determination of the workability of concrete mixtures has been the object of much investigation during the past few years. Pearson and Hitchcock,[3] Smith and Conahey,[4] and Smith,[5] have devised instruments based upon the measurements of the penetration of one or more steel rods through a cylinder of concrete under certain specified forces; Smith and Conahey have also designed an instrument to measure the force required to deform a cylinder filled with concrete. In 1928 the authors[6] completed a series of investigations in which they attempted a contribution to this very important subject of the determination of the workability of concrete mixes, by measuring the power consumption which resulted from the mixing of concrete. Several interesting points developed in discussion of this paper, and it has been in connection with these and with further discussions which have developed during the past year that we have continued our investigations on this subject.

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[1] Materials Engineer, New Hampshire Highway Department, Concord, N. H.

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[3] J. C. Pearson and F. A. Hitchcock, "A Penetration Test for the Workability of Concrete Mixtures with Particular Reference to the Effects of Certain Powdered Admixtures," *Proceecings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 276 (1923).

[4] G. A. Smith and George Conahey, "A Study of Some Methods of Measuring Workability of Concrete," *Proceedings*, Am. Concrete Inst., Vol. XXIV, p. 24 (1928).

[5] G. A. Smith, "The Measurement of Workability of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 505 (1928).

[6] W. F. Purrington and H. C. Loring, "The Determination of the Workability of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 499 (1928).

MATERIALS AND METHODS

Aggregates.—The coarse aggregate used in these tests was gravel, composed of rounded particles and was uniformly graded ranging in size from 0 to 1 in.

The fine aggregate was a local sand, clean and ranging in size from 0 to No. 4.

The aggregates were used after being room dried. Determinations were made of the absorption and moisture in the aggregates in order to calculate the net water necessary to be added so that the correct water-cement ratio might be obtained.

TABLE I.—RESULTS OF TESTS SHOWING RELATIVE WORKABILITY OF CONCRETE USING DIFFERENT PORTLAND CEMENTS.

Flow on brand No. 1 was calibrated to give a flow of 200.
Water-cement ratio 0.80, Abrams' curve A.
Actual power consumption shown in all cases.

Brand	Consistency of Concrete Flow			Normal Consistency of Cement, per cent	Power Consumption, watts		
	No $CaCl_2$	1 per cent $CaCl_2$	2 per cent $CaCl_2$		No $CaCl_2$	1 per cent $CaCl_2$	2 per cent $CaCl_2$
No. 1	200	210	225	25.5	525	592	765
No. 2	201	211	215	23.2	319	440	468
No. 3	203	215	222	23.0	319	485	535
No 4	190	205	220	24.3	400	485	535
No. 5	218	225	230	23.0	225	403	513
No. 6	210	210	215	24.8	403	455	486
No. 7	208	215	225	24.4	375	285	250
No. 8	195	200	210	22.0	403	513	525
No. 9	192	205	213	23.6	455	486	513
No 10	202	210	215	23.2	455	285	252
No. 11	202	195	180	25.7	403	562	650
No. 12	200	219	225	24.6	403	285	225
No 13	168	208	225	25.1	403	562	665
No. 14	178	208	215	23.7	425	513	525
No. 15	205	210	220	24.5	425	340	248
High	218	225	230	22.0	525	592	765
Mean	198	209	217	24.05	394	446	477
Low	168	195	180	25.7	319	285	225

Portland Cement.—The cement used in these investigations was a very uniform brand.

Mixing Concrete.—The concrete was mixed in a vertical axis type of mixer.[1] The mixing operation was continued for 5 minutes after the water had been added. The consistency of the concrete was measured by means of the flow table and the slump test. In the studies of the variations in the workability of 15 brands of cements, brand No. 1 was calibrated to a flow of 200 which was used as a standard while the consistencies for the other brands are shown in Table I.

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[1] W. F. Purrington and H. C. Loring, "The Determination of the Workability of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 499 (1928).

Weight.—The weight of the fine and coarse aggregate, cement and water for each batch in this investigation was 177.15 kg.

Speed of Mixing.—The speed of the mixing paddles was regulated by attaching gears and pinions to the motor shaft. The speeds used in this investigation were 24, 30, 35, 40 and 44 r.p.m.

Readings.—The power readings were taken in all cases at the end of the 5-minute period after the water had been added.

Strengths.—All the mixes in this investigation were designed on the basis of Abrams' curve A, 6 by 12-in. cylinders being used to check all designed mixes for their strength. In all cases the design reached its required strength in 28 days. It was found that the concretes represented in Fig. 5 (batches Nos. 2 and 3) were harsh and that there was a tendency towards segregation. These strengths were 10 per cent below the strengths of the standard cement but had attained the proper design strength in 28 days.

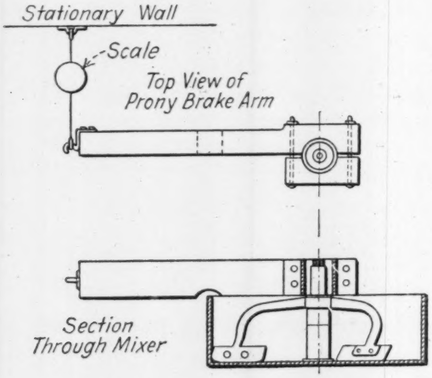

FIG. 1.—Showing Diagram of Prony Brake.

TEST DATA

The Machine Factor Determined by the Application of the Prony Brake:

Mr. W. H. Herschel, in discussion of the paper presented by the authors in 1928,[1] pointed out that it was his opinion that this method of attack on the problem of workability was the correct one. He further stated that it appeared to him that the large amount of friction developed by the machine without any charge—it is between a third and a fourth of the entire power—seemed rather large and doubtless could be cut down.

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[1] *Loc. cit.*

It was with this suggestion in mind that we ran a series of tests to determine the actual power consumption of the machine. We found that the power consumption of the motor was 225 watts when

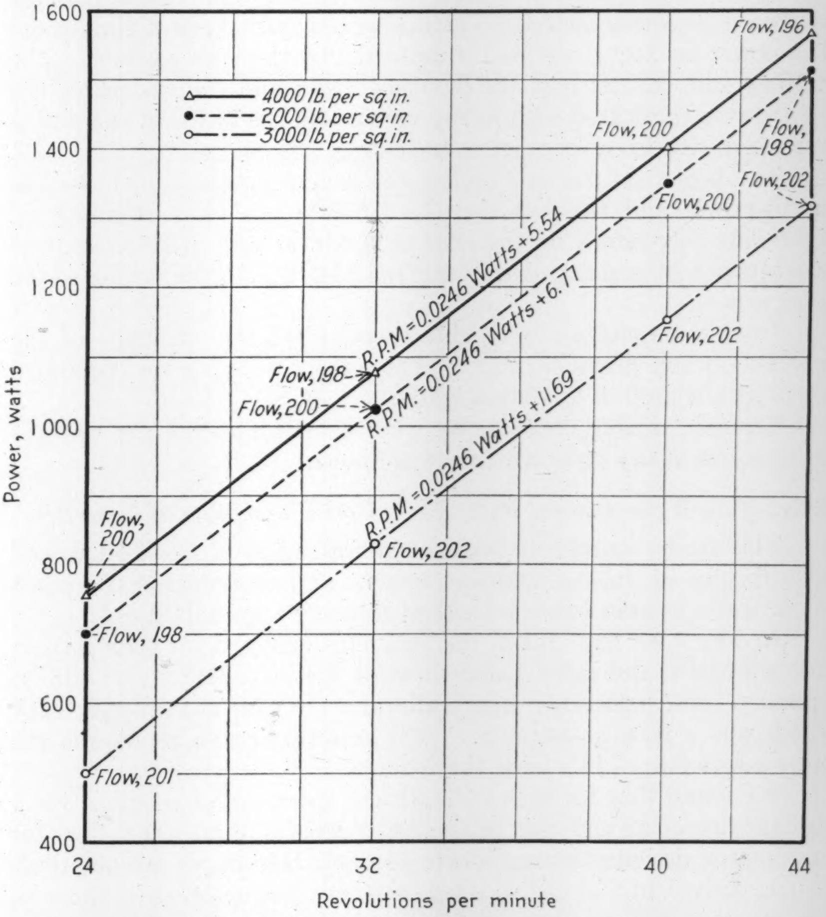

FIG. 2.—Showing the Relation of the Gross Power Output to the Revolutions per Minute.

Design mixes based on Abrams' curve A. Total weight of material each batch, 177.15 kg. Only variable for each batch was speed of mixer. Mixes calibrated to flow of 200 ±5.

running idle, and that the power taken up by the machine in friction loss was 25 watts. For a machine of this size and capable of mixing 5 cu. ft. of concrete, this does not seem such a great loss.

In order that we might measure the actual power consumed in the mixing of the concrete we applied the principle of the prony brake, Fig. 1. This consists of a lever connected to jaws which gripped the revolving pulley attached to the vertical axis of the mixer, so that the friction between the surfaces in contact tends to rotate the arm in the direction in which the shaft revolves. This tendency to rotate is counteracted by attaching the arm to a spring scale. The power for any given load is measured by the scale reading. The rubbing surfaces between the wooden blocks and the surface of the pulley were lubricated with heavy grease and the inside of the pulley was filled with ice to prevent over-heating.

The power output in running the machine, which includes the motor power and the loss through friction, was then obtained by tightening the clamps on the jaws of the lever arm in increments of 50 watts power, and taking the scale readings due to the torque on the lever arm.

In this manner we were able to calculate the efficiency of the machine at any gross wattage. These tests were run on the entire set of speeds used in this investigation.

Thus, in mixing concrete we were able to find the net wattage required when any gross wattage was known.

Effect of the Water-Cement Ratio Law on the Workability of Concrete:

This study consists of taking designed mixes of 2000, 3000, and 4000 lb. per sq. in. concrete in 28 days, and determining the effect of the water-cement relation on their respective workabilities.

In Fig. 2 we have taken the concretes designed for their respective strengths, and have mixed them at speeds of 24, 30, 40 and 44 r.p.m. These concretes were calibrated to the same consistency which was a flow of 200 ± 5. The resulting curve represents the gross power output in mixing the concrete.

We found that for each strength the speed-power relation was a straight line of an equation of the first degree. Since these lines for each of the designed strengths are parallel their slopes are identical. If it is desired to find the wattage or power consumption of either of the mixes or the speed of mixing required to give a predetermined wattage it is only necessary to substitute values in the equations and solve. We found that the concretes gave the most workable mixes in the following order: 3000, 2000 and 4000 lb. per sq. in. concrete.

It has been universally recognized that the richer mixes of concrete have a much higher degree of workability than those which are leaner and that extra cement is often added to a mix to increase workability. The authors were of the same opinion, but this investigation gives results that tend to show that there is an optimum water-cement ratio at which the maximum workability of a concrete mixture is obtained. Below and above this point a concrete is produced which tends to be either of such a texture that there is not enough cement-water paste to lubricate the grains of fine and coarse aggregate, producing a high degree of power consumption due to the friction of the under-lubricated grains in mixing, or a concrete that is over-charged with cement-water paste, which causes a certain tenacity or stickiness of the particles which resists the moving of the particles over one another.

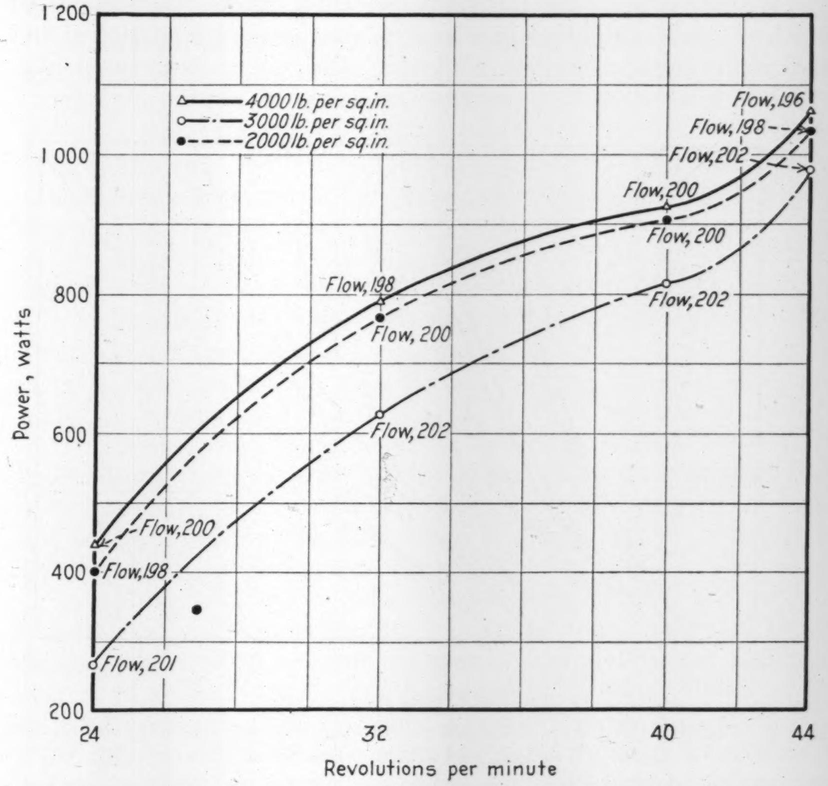

FIG. 3.—Showing the Relation of the Net Power Consumption to the Revolutions per Minute.

Design mixes based on Abrams' curve A. Total weight of material each batch, 177.15 kg. Only variable for each design was speed of mixer. Mixes calibrated to flow of 200 ± 5.

We find that Smith and Conahey[1] gave perhaps the most acceptable definition of the term workability when they stated that "the workability of a concrete is that property which is indicated by the effort required to place the concrete in order to obtain a uniform and homogeneous finished product." The authors are now of the opinion that the richer mixes are more plastic but this does not mean that they are more workable as the above definition of the term would imply.

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[1] *Loc. cit.*

We might say that the term plasticity denotes the ease with which concrete may be molded and finished into its proper form and workability denotes the ease with which the concrete aggregate may be mixed so as to produce a homogeneous mass of uniform consistency.

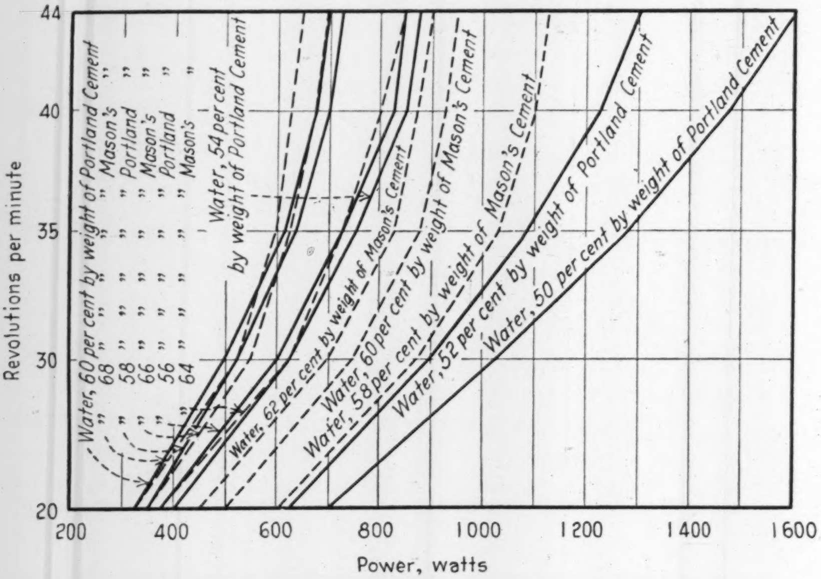

FIG. 4.—Showing the Effect of Consistency on the Power-Workability Relation of Portland and Masonry Cements.

We have taken in Fig. 3 the gross power consumption of each mix and speed as shown in Fig. 2 and have calculated the actual power consumption. It is found that the strengths show the same relation to one another, but that the graph is a curve instead of a straight line. This result is due to the fact that the power-friction loss of the machine from which the net power is calculated decreases with the increase in load.

There is a tendency for the curve of the more workable 3000 lb. per sq. in. design, as measured by the power consumption, to rise at the higher rates of speed. This possibly may be explained when it is considered that the paddles of the mixer are revolving so fast that there is a tendency to break down the cement particles. This would mean that more hydration is taking place with a consequent stiffening of the mix and probably caused an abnormal power consumption.

Effect of the Consistency on the Power-Workability Relation with Portland and Masonry Cements:

Pearson in a progress report of Subcommittee XIV on Workability, prepared for a recent meeting of the Society's Committee C-9 on Concrete and Concrete Aggregates, explained the design of the Pearson horizontal axis mixer which is a joint effort of the Lehigh Portland Cement Co. and the Portland Cement Association. With this instrument, Pearson plotted the flow-pressure curves of cement pastes made from standard portland and masonry cements. On his suggestion the authors ran a series of concretes on a basic 1:2:3½ mix at consistencies ranging from very dry (flow 130) to very wet (flow 260 +).

As shown in Fig. 4 the concrete was mixed with the total water of 50 per cent by weight of portland cement. At the 2-minute interval after we added the water we took the power reading and added an increment of water equivalent to 2 per cent by weight of the cement. In a like manner we added increments of water and took readings until we had a total of 60 per cent of water to the weight of the cement. The consistency of the concrete at this point could not be measured on the flow table, and any further additions of water were useless for our purpose.

In a like manner, we substituted masonry cement for portland cement used in the preceding study. It was found necessary to add an equivalent of 58 per cent by weight of water to the weight of cement to obtain a consistency as measured by the flow table of 130 as in the preceding test. Water was then added in increments of 2 per cent by weight of the cement and power readings were taken as before until we had a total water content equivalent to 68 per cent by weight of the cement.

The resulting curves are of the same general type as those obtained by Pearson in the study of cement pastes. We found as would be expected that the drier the mix the more power consumption necessary to mix the materials and *vice versa*.

Variations in the Workability of Standard Portland Cements:

In the discussion of the "Variations in Standard Portland Cements," P. H. Bates[1] under the title of "Proportioning and Workability" states: "However, none of these (referring to the investigators on the workability of concrete) has considered how much different makes of cement would effect their results; neither is it possible to correlate their results so as to determine if the cement has been a factor."

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[1] P. H. Bates, "Variations in Standard Portland Cements," Report of Committee 202, *Journal*, Am. Concrete Inst., Vol. XXVI, December, 1929, p. 65.

The authors found in 1928, in the investigation of seven different brands of cement by use of the vertical axis type of mixer, that, under identical conditions except that the brand of cement was varied, certain brands showed a higher degree of workability than others. We have now completed an investigation covering 15 representative brands of portland cement.

In Table I are given the tabulated results of an investigation on the effect of cement upon the workability of concrete. The only variable in this investigation was the cement and the test results tabulated are the average of 5 batches of concrete mixed on different days. The authors felt that by this method of test any variation liable to enter the test would be averaged. The same operators covered this entire investigation, and had the same duties.

We found in this series of tests that the power consumption of each brand did not vary more than 2 per cent from day to day, and that the variation in the determination of the degree of consistency by means of the flow table was 15 per cent. In several of the brands of cement which were included in the authors' investigation in 1928, it was found that the variation in the power consumption (net) was no higher than 20 per cent and as low as 3 per cent.

It was found in this study that the concrete-making characteristics of certain brands of cement varied considerably. Some brands seemed to act as a repellent towards water and in these cases we note a low power consumption. Other brands of cement acted in the opposite manner.

The phenomenon which causes cements seemingly to repel water has a tendency to change from time to time. A pertinent example of this is found in a certain brand of cement which the authors examined in 1929 and found that it had this characteristic. In 1930 this cement showed that the reverse was true, this repelling action had disappeared entirely and there was no change in the cement in so far as we were able to determine by means of physical tests. The manufacturer when informed of this fact checked back and could give no reason why it should be different from the preceding sample.

Effect of Calcium Chloride on the Workability of Cements.—A like investigation on the effect of calcium chloride on standard brands of portland cement was carried out on the 15 brands of cement in the

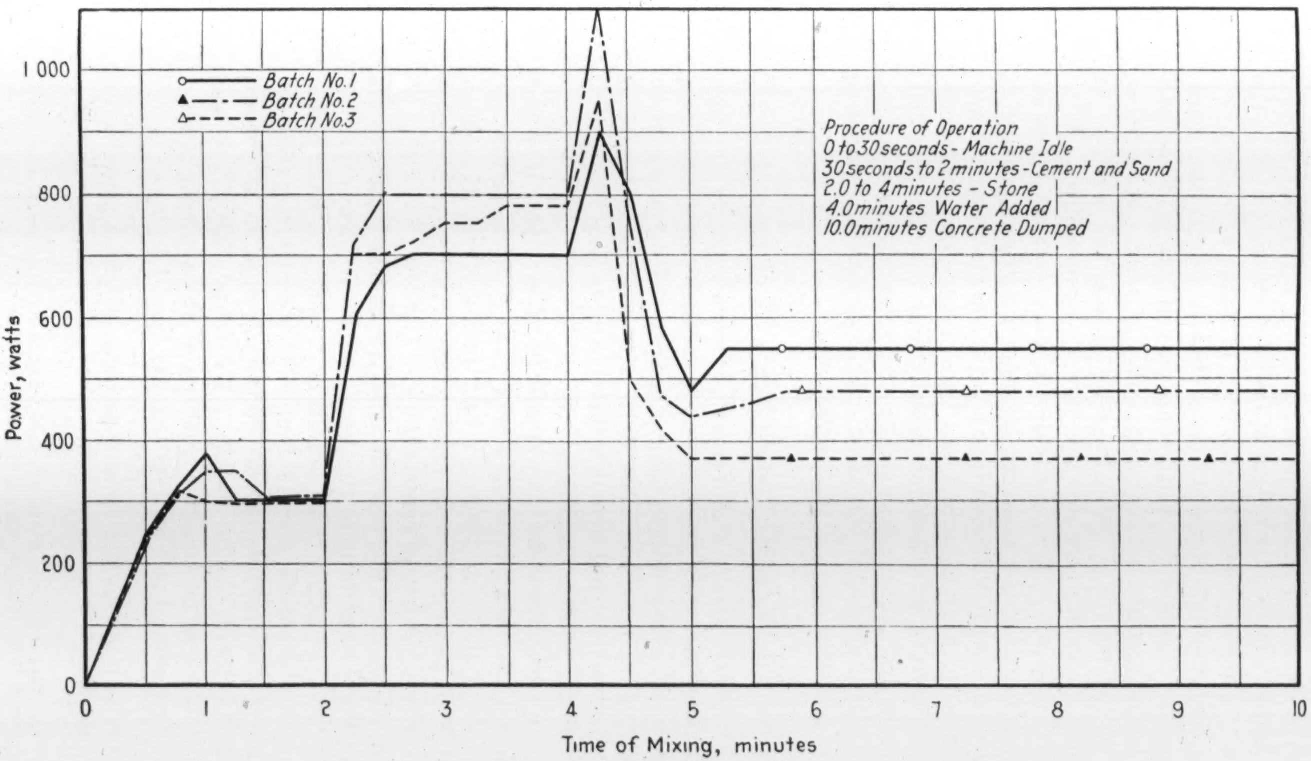

FIG. 5.—Showing the Power-Workability Relation of Three Brands of Cement.

Total water includes water of absorption. The only variation is the brand of cement used in each batch. Total weight (dry and rodded), 177.15 kg. Design based on Abrams' curve A.

	Compressive Strength, lb. per sq. in.	Design Mix	Re-Design Mix	Fineness Modulus of Sand	Fineness Modulus of Stone	Water-Cement Ratio	Total Water, gal.	Slump, in.	Flow	Brand
Batch No. 1........	3000	1:2.42:3.33	1:1.90:3.33	2.72	8.30	0.80	6.065	3¼	200	Laboratory Standard
Batch No. 2........	3000	1:2.42:3.33	1:1.90:3.33	2.72	8.30	0.80	6.065	7¾	260	No. 2
Batch No. 3........	3000	1:2.42:3.33	1:1.90:3.33	2.72	8.30	0.80	6.065	5½	225	No. 1

same manner as described above, the only change being that 1 and 2 per cent of calcium chloride by weight of the cement was added to the mixing water. These results are also shown in Table I.

We find that the addition of calcium chloride affects the workability of cements differently. With some cements the addition of 1 and 2 per cent of calcium chloride increases the power consumed in the mixing of the concrete, while in other brands the addition of the admixture materially lessens the power consumption. With those brands where we find an increase in the power consumption there is a tendency for the concrete to have a certain tenacity or stickiness which is the predominant feature of the richer mixes. There is no question in the authors' minds but that in some cases the addition of this admixture increases the plasticity of the resulting concrete, but we also find that the workability of the concrete, as measured by its power consumption, is increased over that power required to mix the same concrete without this admixture.

The Economic Application of the Vertical Axis Type of Mixer:

Mr. P. H. Bates[1] states: "However, . . . since cements are now being sold on the basis that they are more 'plastic' or will produce more 'workable' plastic products than others, it will be necessary to devise apparatus to determine not only whether the cements, as pastes, are as advertised but also whether they produce the quality claimed for them in mortars and concretes.

"There are two ways of looking at this problem. One is to test the material, so that the manufacturer may make good his claims and on the other hand that the consumer may be convinced that he is getting what he is paying for. In other words, can he get a greater yardage of concrete per bag of cement?"

By the application of the vertical axis type of mixer the authors desire to contribute something to this phase of the problem.

In Fig. 5 we have taken three brands of cement and have mixed them under identical conditions, the brand of cement being the only variable. One of the cements in this investigation is an advertised plastic portland cement (brand No. 2). We found that there was dissimilarity in the concrete making qualities of the cements studied and these are represented in Fig. 5 as batches Nos. 1 to 3.

Batch No. 1, laboratory standard cement, shows a power consumption of 550 watts, a slump of 3¼ in. and a flow of 200.

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[1] P. H. Bates, "Variations in Standard Portland Cements," Report of Committee 202, *Proceedings*, Am. Concrete Inst., Vol. XXVI, December, 1929, p. 65.

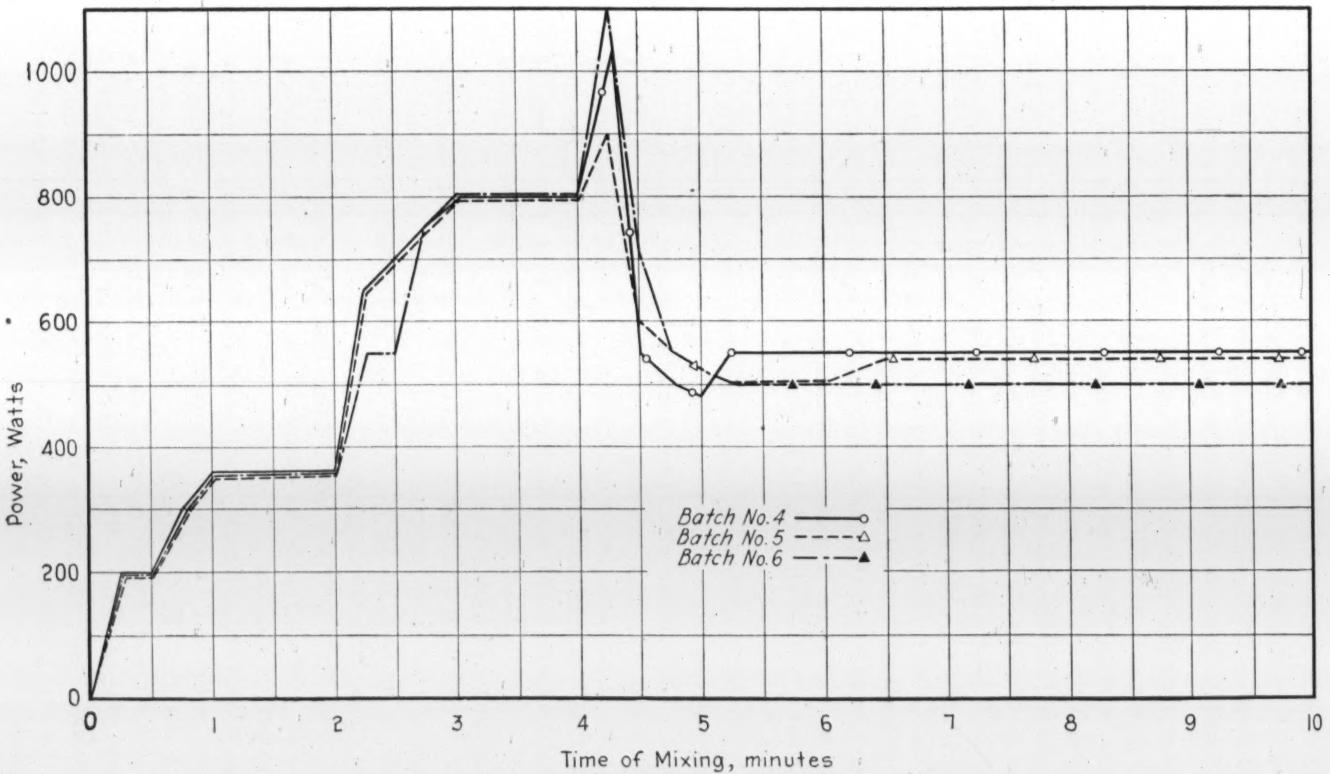

FIG. 6.—Showing the Power-Workability Relation of the Three Brands of Cement at the Same Consistency.

Total water includes water of absorption. All mixes based on 3000 lb. per sq. in. design.

Redesigned batch Nos. 5 and 6 to account for variance of slump.

		Compressive Strength, lb. per sq. in.	Design Mix	Re-Design Mix	Fineness Modulus of Sand	Fineness Modulus of Stone	Water-Cement Ratio	Total Water, gal.	Slump, in.	Flow	Brand
Batch	No 4	3000	1:1.90:3.33	1:1.90:3.33	2.72	8.30	0.80	6.065	$3\frac{1}{4}$	200	Laboratory Standard
Batch	No. 5	3000	1:1.90:3.33	1:2.13:3.52	2.72	8.30	0.80	6.123	3	202	No. 1
Batch	No 6	3000	1:1.90:3.33	1:2.19:3.69	2.72	8.30	0.80	6.128	$3\frac{1}{4}$	205	No 2

Batch No. 2, brand No. 2, shows a power consumption of 370 watts, a slump of 7¾ in. and a flow of 250.

Batch No. 3, brand No. 1, shows a power consumption of 480 watts, a slump of 5½ in. and a flow of 225.

It is seen that the cements of batches Nos. 2 and 3 show a marked increase in flow and workability over the brand of cement used in batch No. 1. The consumer may well take advantage of certain brands of cement which show this characteristic, especially when using chutes and around steel reinforcement. It would mean that at a mix which would give him ordinarily a 3 to 4-in. slump he would obtain a consistency suitable for use without decreasing the amount of fine and coarse aggregate which he would have had to do if he used the cement in batch No. 1. Decreasing aggregates means a higher cement content and this means greater cost per cubic yard of concrete. The engineer is benefiting in the use of this type of cement in that he is enabled to obtain a concrete of a lower water-cement ratio, with its resulting good qualities, than could be obtained with the cement used in batch No. 1.

In Fig. 6 the same brands and mixes were taken as in Fig. 5, except that batches Nos. 2 and 3 were built up to the same degree of consistency. These mixes are represented by batches Nos. 4 to 6.

We find that in order to bring batch No. 5 using brand No. 1 cement to the same consistency of batch No. 4 which is the same as batch No. 1, it was necessary to increase the proportions of the dry and rodded mix of 1:1.90:3.33 in batches Nos. 1 to 4 to a mix of 1:2.13:3.52 or an increase in the sum of the total volumes of coarse and fine aggregate of 8.04 per cent.

In batch No. 6 using brand No. 2 cement we found it necessary to increase the original proportions of 1:1.90:3.33 to a mix of 1:2.19:3.69 or an increase of 12.43 per cent in the sum of the total volumes of coarse and fine aggregate.

From these tests we have found that these advertised "plastic" or "workable" cements may be examined in concrete and their advertised properties checked.

These advertised "plastic" or "workable" cements may be examined as pastes and mortars by the use of an apparatus devised by one of the authors (H. C. Loring) in 1926. This instrument consisted of an ice cream freezer operated on the same principle as the vertical axis type of mixer. The cement paste or mortar is mixed in this instrument and its degree of "plasticity" or "workability" measured by the power consumption as determined by an ammeter and voltmeter.

By the use of the vertical axis type of mixer and the instrument described above, the authors feel that advances may be made in the study of the plastic and workable cement pastes, mortars and concrete so that they may be investigated relative to their advertised advantages.

CONCLUSIONS

The machine described above has many advantages for the study of workability. It utilizes the principle of shear. Results upon this machine can be duplicated without difficulty. As a laboratory instrument it may appear crude but when we consider the fact that it allows us to work with relatively large quantities of materials this crudity is not so apparent. The machine can be utilized to study the speed-power relation which we believe is the important thing to consider when workability is under discussion. Variations in mix, such as different water-cement ratio designs and consistencies, can be studied and their results can be reported in definite terms of power consumption.

DISCUSSION

Mr. E. C. Shuman[1] (*presented in written form*).—The results given in the paper by Messrs. Purrington and Loring are very interesting and are a valuable contribution to much needed data on the subject of workability of concrete. The general types of indicator curves the authors have given agree closely with those our company obtained in some cooperative tests at Purdue University in 1920. The tests by Messrs. Purrington and Loring are, however, much more complete and of greater significance than those we have conducted with power measuring equipment. While the information we secured in the Purdue tests was interesting and informative to some extent, the method was not considered to be of practical significance for field use.

In most of the consistency (which term I shall use for want of a better) indicators with which I am familiar the application has been to concrete already mixed and discharged from the mixing apparatus. We have attempted to do more than this since we are interested in the problem primarily from the "field" standpoint. Our attempt has been to develop a consistency indicator as a part of the concrete mixer which will indicate the consistency of the concrete during the mixing operation. It is well known that even though materials are batched by weight and water is measured accurately, noticeable variations in the consistency of the concrete in various batches are found. Small variations in consistency as a rule are not of great importance but the variations encountered in the field are often appreciable. There are certain types of concrete structures where variations in consistency are of greater concern than the variations in strength. In other words, the placeability of the concrete is as important and sometimes more important than the strength. Therefore, it is desirable to produce concrete in which successive batches are of the same consistency, provided of course that the corresponding strength variations are within reasonable limits.

In designing the mechanical operation of the swing chute for discharging concrete from the mixer, it was found that wide variations in the force required to move the chute were obtained. For concretes of wet consistency one man could swing the chute without difficulty but for concretes of dry consistency three men were often required for the discharge operation. From this observation it was thought that by measuring the force with which concrete fell on an apparatus in the drum, an indication of the consistency of the concrete would be obtained.

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[1] Research Engineer, Koehring Division, National Equipment Corp., Milwaukee, Wis.

In the preliminary tests, a straight $\frac{1}{4}$ by $1\frac{1}{2}$-in. bar, supported outside of the discharge end of the mixer, was projected into the mixer so that concrete from the buckets fell directly on it. This is shown schematically in the accompanying Fig. 1. The first results, plotted in the accompanying Figs. 2 and 3, show the relation between indicator reading and slump both for a straight bar and a plate impact surface.

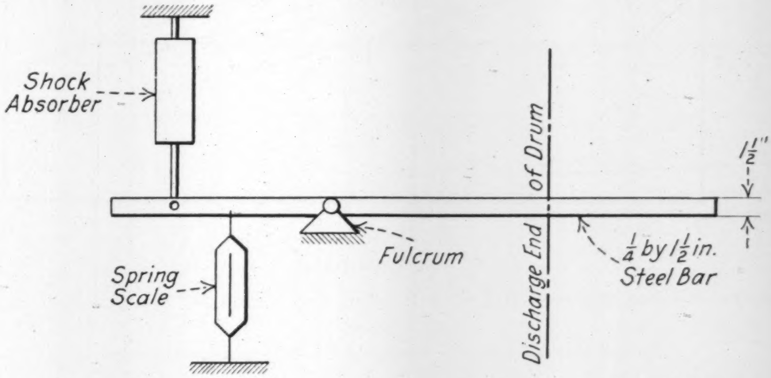

FIG. 1.—Schematic Diagram Showing Straight Bar Consistency Indicator.

Figure 2 shows that when the straight bar was held edgewise in the stream of concrete a straight line relationship between indicator reading and slump was found. However, when a 4 by 6-in. plate was attached to the end of the straight bar, a curved relationship was found as shown in Fig. 3. Apparently this latter result is somewhat in accord with the findings of Messrs. Purrington and Loring since they showed a higher power consumption for the 3000 lb. per sq. in. concrete than for the 2000 or 4000 lb. per sq. in. concrete. Since the curves in Fig. 3 were obtained from concretes of different water contents and consequently of different strengths, there is some similarity between our results and those of the authors. For example, the 1:$1\frac{1}{2}$:2 mix has a lower reading for a 1-in. and a 6-in. slump than for a 3-in. slump. It was observed that this mix with a 1-in. slump had a dry, plastic appearance, with a 6-in. slump it had a more fluid appearance, and with about a 3-in. slump it was decidedly sticky.

To this extent at least their consistency indicators and ours are in agreement.

The change in relation between indicator reading and consistency as measured by slump, due to the effect of the plate, necessitated

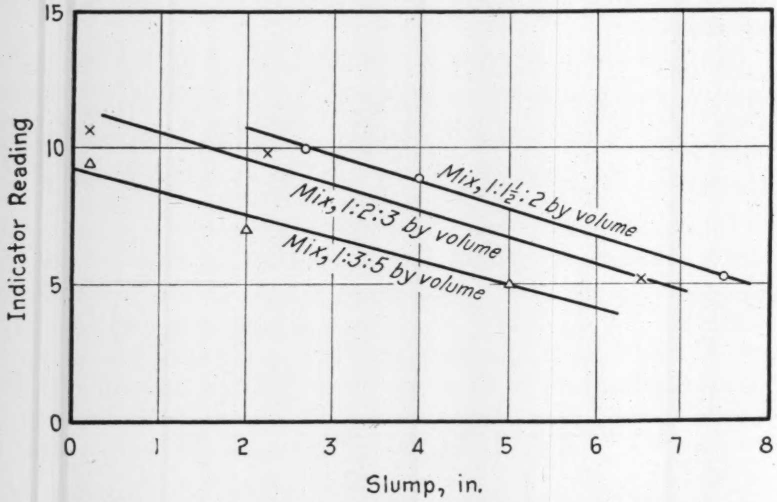

FIG. 2.—Relation Between Indicator Reading and Slump for Straight Bar Impact Surface.

Time of mixing, 3 minutes. Straight bar, ¼ by 1¼ in., impact surface.

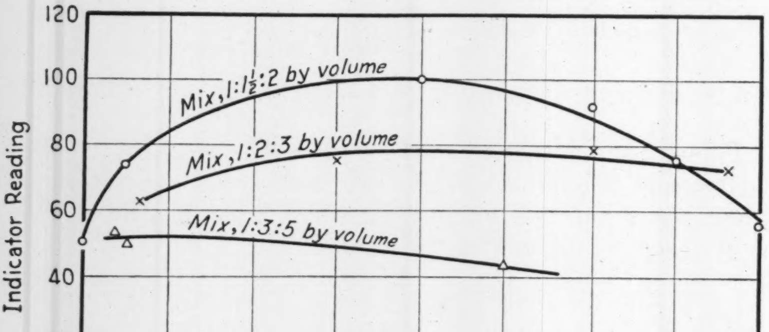

FIG. 3.—Relation Between Indicator Reading and Slump for Plate Impact Surface.

Time of mixing, 3 minutes. Plate impact surface 4 by 6 in. on end of straight bar used in Fig. 2.

further tests because for field use the indicator would have to show constantly decreasing readings as the consistency of the concrete became wetter. In these tests several indicators were tried with bars entering the drum from both the charge and discharge ends. In the observation of the mixing action it was found that for a given mix the concrete was carried by the blades and buckets in different amounts and directions depending on the wetness of the concrete. This influenced the readings because of the change in effective lever arm of the force of the falling concrete, and it was concluded that best results were obtained with the apparatus supported on or entering the discharge end of the drum.

In the preliminary studies Koehring 5-S and 10-S construction mixers were used. In our latest development, the indicator has been attached to a 27-E paver with the force of the concrete on the bar converted to oil pressure and read on an ordinary sensitive oil gage.

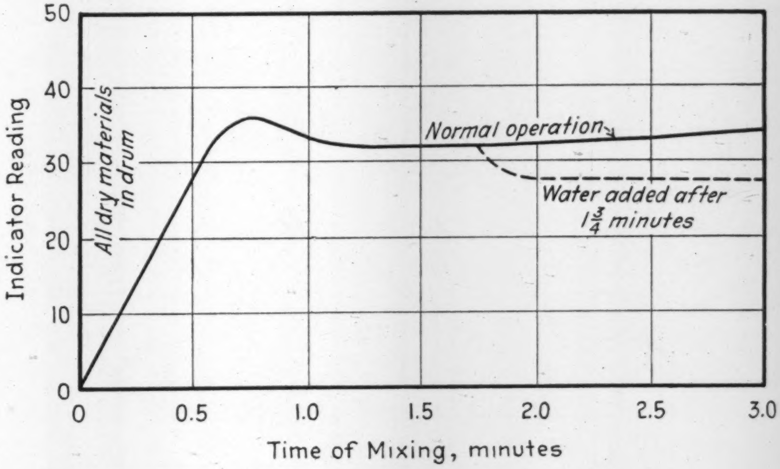

FIG. 4.—Typical Indicator Curve During Mixing Operation.

Just what the property of the concrete might be called that we are measuring is immaterial. We know that the water is the only controllable variable at the mixer, and that by varying the water in small quantities, we are able to produce successive batches of the same consistency. At least they are the same as judged by eye. We do not claim that the instrument in its present form measures workability. Workability requires a more satisfactory definition than we have at present. However, for a given mix, this consistency indicator will produce successive batches that are essentially alike so far as placing of the concrete is concerned. Other means would be required to determine the absolute workability of the mix but once the mix producing the desired workability is established, the consistency indicator is intended to aid in the production of uniform batches of such concrete.

Several significant features of this apparatus should be noted. For example, the indicator will show when concrete is uniformly mixed. With a time record, the maximum point is reached in 40 to 45 seconds depending on various factors. In this way it could be used for comparing the time of mixing of different mixers. A typical indicator curve for rate of mixing is shown in Fig. 4. Additions of water require about 15 seconds for thorough incorporation as shown by the dotted line in the figure. Other variables such as time of entrance of mixing water, rate of flow of water, rate of flow of materials, order of charging materials or anything which will affect the time required for uniform mixing, are all reflected by the indicator.

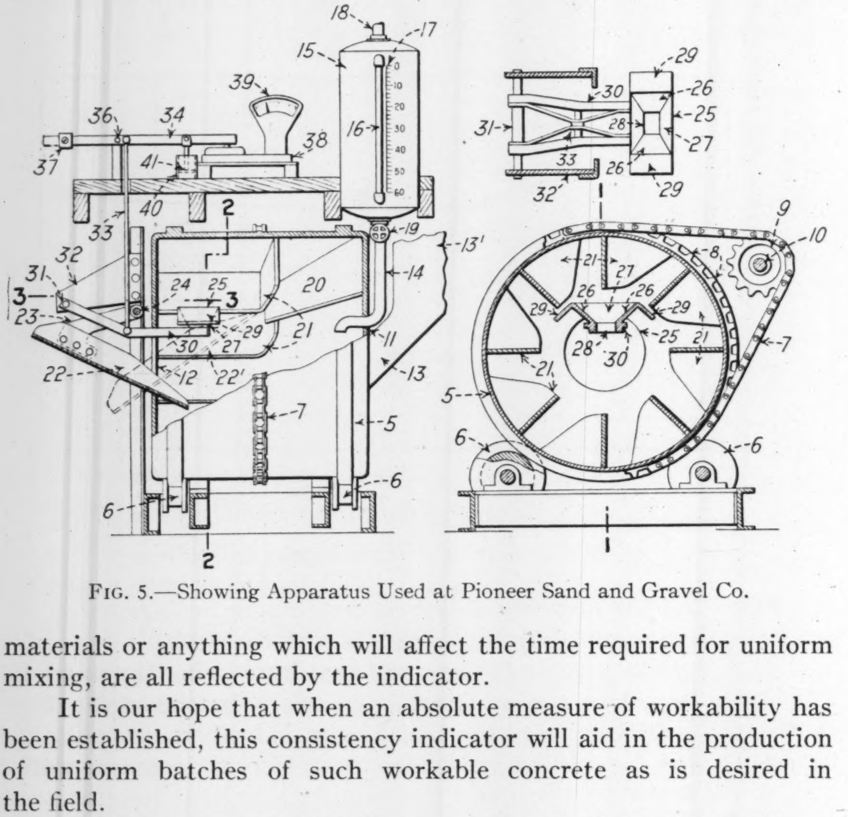
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FIG. 5.—Showing Apparatus Used at Pioneer Sand and Gravel Co.

It is our hope that when an absolute measure of workability has been established, this consistency indicator will aid in the production of uniform batches of such workable concrete as is desired in the field.

MR. I. L. COLLIER.[1]—Mr. Perry, engineer for the Pioneer Sand and Gravel Co. in Seattle, is using an apparatus in their central mixing plants very similar to that with which Mr. Shuman is experimenting. Instead of using the bar or pans as Mr. Shuman suggested, they have in the mixer a frustum of a pyramid, open at top and bottom, as shown in the accompanying Fig. 5. When the mixer is in operation approximately 80 per cent of the batch is discharged through this orifice. The friction of the concrete flowing through the metal orifice is considered a measure of the workability of the concrete and is measured in several ways, such as by means of a platform scale or by means of a pressure gage and an automatic recording device. This recorder not only records the workability of the concrete but also the time consumed in mixing. Thus a complete record of each batch isobtained. Figure 6 is a reproduction of one of the charts.

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[1] Assistant Professor of Civil Engineering, University of Washington, Seattle, Wash.

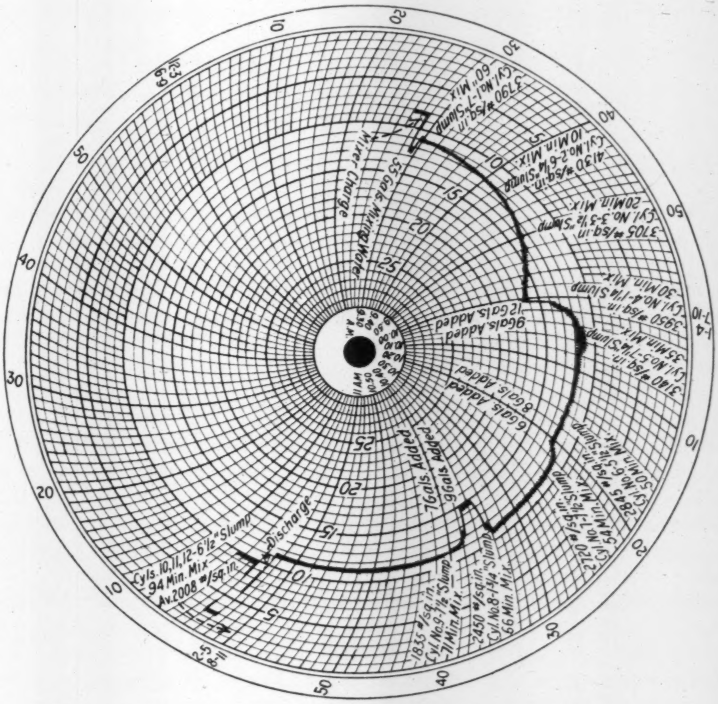

FIG. 6.—Showing a Chart for an Overmixing Test of a 2-yd. Batch of 1:2:3 Concrete.

TESTS OF PLAIN AND REINFORCED HAYDITE CONCRETE

By F. E. Richart[1] and V. P. Jensen[2]

Synopsis

The paper gives information regarding structural properties of poured Haydite concrete, such as is now being used in building construction. The mixtures include concretes made with fine and coarse Haydite aggregates, natural sand and coarse Haydite, and, for comparison, sand and gravel or broken limestone. Data of 75 beam tests, 27 bond pull-out tests and nearly one thousand 6 by 12-in. cylinder tests are given. Studies were made of properties of the aggregates, workability, yield, unit weight, compressive strength and modulus of elasticity of the concrete and resistance to bond and diagonal tension in beams.

Concrete was made with Haydite aggregates with no particular departure from ordinary methods. The usual mixing procedure was used and no difference was noted in the work required to place the material in forms and around reinforcement for beams of gravel, limestone and Haydite concrete. Gravel and Haydite concretes as used follow approximately the same relation between water-cement ratio and compressive strength. There was no indication that the strength of any of the mixtures was limited by the strength of the aggregate particles. The resistance to bond and diagonal tension was about the same proportion of the compressive strength for gravel and Haydite concretes. The modulus of elasticity of Haydite concrete is markedly lower than that of gravel concrete. The unit weights of concrete vary considerably for different richnesses and proportions of the aggregates: values as low as 93 lb. per cu. ft. for all-Haydite concrete and 112 lb. per cu. ft. for concrete made with sand and coarse Haydite, were obtained.

Introduction

The use of burnt-shale aggregate, of the type known as Haydite, has been confined largely to the manufacture of concrete products. Some use was made of burnt-shale aggregates in reinforced-concrete ship construction during the war, but there is little information available from this source. The present tests were made to furnish data on structural properties of poured Haydite concrete, which is now finding increasing use in reinforced-concrete building construction. Not only is information needed as to the properties of the finished concrete, but there is also a demand for information as to proper

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TABLE I.—UNIT WEIGHT AND MOISTURE CONTENT OF AGGREGATES.

Lot	Kind of Aggregate	Aggregate Used in Series	Unit Weight, lb. per cu. ft.			Moisture Content when Received, per cent by weight
			Loose Dry	Rodded Dry [a]	Loose Moist	
No. C-1	Coarse Haydite	....	42	46	..	7.6
No. C-2	Coarse Haydite	....	43	47	..	5.8
No. C-3	Coarse Haydite	B. B.	41	45	..	3.3
No. C-4	Coarse Haydite	....	45	49	..	5.9
No. C-6	Coarse Haydite	1, A-2, A-3, S, B. B., T	45	48	46	6.0
No. C-7	Coarse Haydite	D. T.	44	48	..	6.3
No. A-1	Fine Haydite	....	50	..	..	9.8
No. A-2[b]	Fine Haydite	A-2	55	..	51	27.0[b]
No. A-3	Fine Haydite	A-3, B. B., T	54	60	..	2.9
No. A-4	Fine Haydite	1, D. T.	56	64	..	8.3
No. G-1	Gravel	1	99	106	..	....
No. G-2	Gravel	G-2, B. B.	95	102	..	....
No. G-3	Gravel	D. T.	100	108	..	....
No. L-1	Limestone	1	88	98	..	....
No. S-1	Natural Sand	1	105	112	..	....
No. S-2	Natural Sand	G-2, S, T, B. B.	107	113	..	....
No. S-3	Natural Sand	D. T.	105	111	..	....

[a] A.S.T.M. Standard Method of Test for Unit Weight of Aggregate for Concrete (C 29 – 27).
[b] This lot from outdoor stockpile.

TABLE II.—SIEVE ANALYSES OF AGGREGATES.

Lot	Kind of Aggregate	Retained, per cent by weight									Fineness Modulus
		$\frac{3}{4}$-in. Sieve	$\frac{1}{2}$-in. Sieve	$\frac{3}{8}$-in. Sieve	No. 4 Sieve	No. 8 Sieve	No. 14 Sieve	No. 28 Sieve	No. 48 Sieve	No. 100 Sieve	
No. C-1	Coarse Haydite	0	1	..	83	96	98	..	..	..	....
No. C-2	Coarse Haydite	0	2	..	67	95	98	..	..	..	....
No. C-3	Coarse Haydite	0	5	..	78	96	97	..	..	..	....
No. C-4	Coarse Haydite	0	3	..	60	95	98	..	..	..	....
No. C-6	Coarse Haydite	0	6	22	72	96	99	..	..	..	5.89
No. C-7	Coarse Haydite	0	4	39	92	99	..	..	..	..	6.30
No. C-8	Coarse Haydite	0	2	30	82	94	94	..	..	..	6.00
No. A-1	Fine Haydite	0	0	0	0	11	52	72	80	86	3.01
No. A-2	Fine Haydite	0	0	0	0	9	43	65	78	85	2.80
No. A-3	Fine Haydite	0	0	0	0	11	46	64	76	84	2.81
No. A-4	Fine Haydite	0	0	0	0	6	40	60	72	81	2.59
No. G-1	Gravel	0	..	37	92	97	98	..	..	..	6.24
No. G-2	Gravel	0	7	22	92	99	99	..	..	..	6.13
No. G-3	Gravel	4	16	28	83	97	..	..	..	..	6.12
No. L-1	Limestone	0	..	20	82	94	96	..	..	..	5.92
No. S-1	Natural Sand	0	0	0	2	16	38	64	89	98	3.07
No. S-2	Natural Sand	0	0	0	2	16	38	64	89	98	3.07
No. S-3	Natural Sand	0	0	0	3	14	35	67	93	99	3.11

TABLE III.—APPARENT SPECIFIC GRAVITY AND ABSORPTION OF AGGREGATES.

Each figure is the average of 3 determinations.
Portion of aggregates retained on No. 4 sieve used.

SAMPLE FROM	APPARENT SPECIFIC GRAVITY	VOIDS, PER CENT	ABSORPTION IN 15 MINUTES, PER CENT BY WEIGHT
Lot No. C-1	1.30	0.43	4.9
Lot No. C-2	1.28	0.41	5.4
Lot No. C-3	1.25	0.43	5.2
Lot No. C-4	1.32	0.41	5.1

proportioning, mixing methods, workability and placeability of the fresh concrete and as to methods of curing.

This paper presents a progress report of an investigation being made at the Materials Testing Laboratory, University of Illinois, in cooperation with the Western Brick Co., Danville, Ill., manufacturers of "Western" Haydite aggregates. The work is being carried on under the administrative direction of Dean M. S. Ketchum, Director of the Engineering Experiment Station, and Professor M. L. Enger, Head of the Department of Theoretical and Applied Mechanics, University of Illinois. Acknowledgment is made to Mr. I. N. Doughty, General Superintendent, and Mr. Frank Payne, Engineer, of the Western Brick Co. for advice and assistance in the testing program.

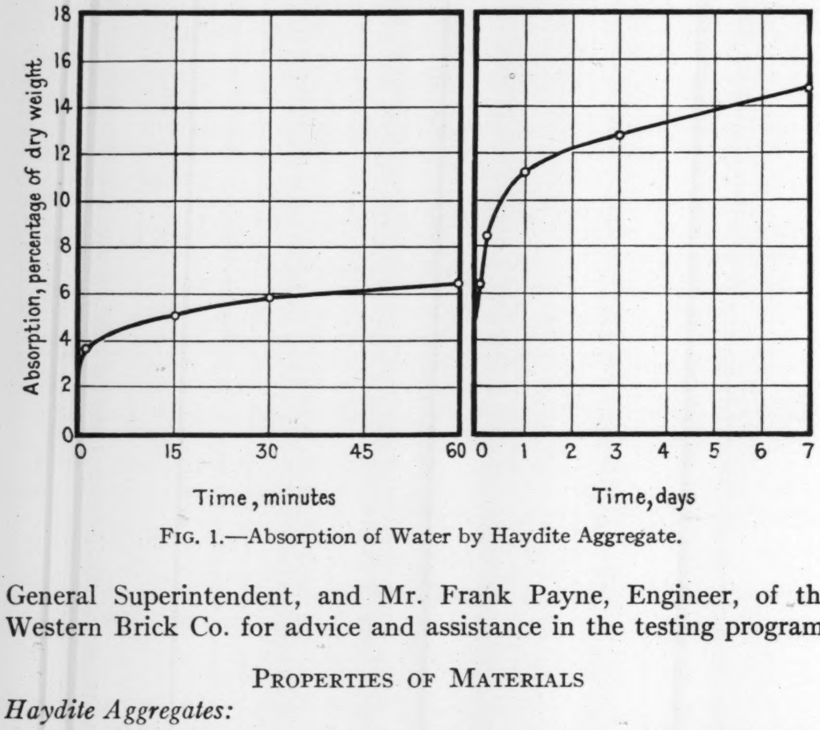


FIG. 1.—Absorption of Water by Haydite Aggregate.

PROPERTIES OF MATERIALS

Haydite Aggregates:

The Haydite tested all came from one source, the plant of the Western Brick Co. near Danville. The sizes used were the "A" size, containing material passing the $\frac{3}{16}$-in. round-hole screen, and the "C" size, containing material retained on the $\frac{7}{32}$-in. and passing the $\frac{3}{4}$-in. screen.

Properties of six lots of "C" size and four lots of "A" size Haydite are given in the following tables. These lots represent ordinary plant run of material as selected at different times. Table I gives the unit weight of the material under different conditions of moisture and tamping. The moisture content of the material as received from the plant is also shown in the table.

Table II gives sieve analyses of the material of the lots noted above, as obtained by the use of Tyler Screen Scale Sieves.

Table III gives values of the apparent specific gravity of the "C" size Haydite as determined by displacement methods. The voids and 15-minute absorption of the material are also given. As a study of the porosity of the material, several samples were ground in a ball mill and determinations of the specific gravity of the powdered material were made by the use of a Le Chatelier flask with kerosine. The specific gravity of the material passing a No. 200 sieve averaged 2.56, while that of the material between the No. 100 and No. 200 sieves was 2.37. Reference to the apparent specific gravity in Table III indicates that the "C" size aggregate contains roughly 50 per cent of pore space, although the vesicular structure permits only about a 5-per-cent absorption (by weight) in fifteen minutes.

TABLE IV.—TENSION TESTS OF STEEL.

Each figure is the average of 3 or more tests.

SIZE	USED IN SERIES	YIELD POINT, LB. PER SQ. IN.	TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 8 IN., PER CENT	REDUCTION OF AREA, PER CENT
5/8-in. Round............	1	39 100	70 000	23	51
1 1/8-in. Square...........	B.B.	63 100	110 200	15	11
1/2-in. Round............	B.B.	48 000	72 700	23	34
1/2-in. Square............	B.B.	34 000	54 900	29	40
1-in. Round............	D.T.	37 600	58 900	31	35
1/2-in. Round............	D.T.	52 800	83 900	18	41

Average results of absorption tests on six to twelve samples from the lots of coarse Haydite in Table III, covering periods of time varying from 1 minute to 7 days, are shown in Fig. 1. It is seen that a considerable part of the 15-minute absorption takes place in the first minute of immersion; it is also seen that the absorption was increasing at a fairly uniform rate at the end of the 7-day period. Tests of absorption of fine Haydite, Lot A-4, show an absorption of 12 per cent by weight in 15 minutes, 14 per cent at 1 hour and 18 per cent at 3 hours. Both fine and coarse aggregates were initially dry.

Sand, Gravel and Limestone:

The sand and gravel used were from pits on the Wabash River at Covington, Ind. The broken limestone came from Kankakee, Ill. Properties of these aggregates are included in Tables I and II.

TABLE V.—TESTS OF BEAMS, SERIES 1.

Aggregates used: Sand, S-1; gravel, G-1; limestone, L-1; fine Haydite, A-4; coarse Haydite, C-6. See Tables I and II.
Proportions by loose, dry volumes, except for coarse Haydite which contained 6 per cent moisture.
Additional moisture allowances were: for sand, S-1, and gravel, G-1, 1 per cent; for limestone, L-1, 3 per cent; for coarse Haydite, C-6, 3 per cent; for fine Haydite, A-4, 18 per cent.
Values for cylinders are average of 3 tests.

Mix and Water-Cement Ratio	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	28-Day Tests, Beam				28-Day Tests, 6 by 12-in. Cylinders	
				Ultimate Load,[a] lb.	Load[a] at Yield Point, lb.	Deflection at Load of 13,000 lb., in.	Measured f_s at Yield Point, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.
CONCRETE MADE WITH NATURAL SAND AND GRAVEL AGGREGATES									
$1:1\frac{3}{4}:2\frac{1}{4}$ … $\frac{W}{C} = 0.90$.	8.8	243	145.8	16 800	15 500	0.151	38 100	4790	3 920 000
	8.7	230	146.0	15 700	15 100	0.158	38 100	4710	4 010 000
	9.8	246	145.5	……	……	…..	……	4690	3 910 000
Average…..	8.8	237	145.8	16 300	15 300	0.155	38 100	4730	3 950 000
$1:2:3$ ….. $\frac{W}{C} = 1.0$..	8.9	234	146.4	15 700	14 600	0.157	38 400	3300	3 800 000
	8.7	254	146.4	17 900	14 700	0.169	43 800	4100	3 690 000
	8.0	240	147.4	15 900	14 800	0.155	37 500	4200	4 100 000
Average…..	8.5	243	146.7	16 500	14 700	0.160	39 900	3870	3 860 000
$1:2\frac{1}{2}:3\frac{1}{2}$ … $\frac{W}{C} = 1.20$.	8.4	238	146.8	16 500	15 800	0.163	41 400	2990	3 490 000
	8.5	247	146.5	16 700	15 600	0.169	42 000	3130	3 700 000
	8.0	243	146.0	15 800	15 300	0.171	39 300	3300	3 910 000
Average…..	8.3	243	146.4	16 300	15 600	0.168	40 900	3140	3 700 000
CONCRETE MADE WITH NATURAL SAND AND COARSE HAYDITE									
$1:1\frac{3}{4}:2\frac{1}{4}$ … $\frac{W}{C} = 0.94$.	8.5	253	117.1	16 000	14 500	0.176	37 200	4150	2 630 000
	8.7	256	117.4	15 400	14 100	0.179	31 800	3920	2 680 000
	8.8	252	118.3	15 700	14 500	0.180	37 200	4400	2 550 000
Average…..	8.7	254	117.6	15 700	14 400	0.178	35 400	4160	2 620 000
$1:2:3$ ….. $\frac{W}{C} = 1.02$.	6.8	222	115.0	14 900	14 700	0.193	39 600	3500	2 620 000
	7.7	250	115.6	15 000	14 100	0.161	41 400	3530	2 330 000
	8.0	248	116.0	16 200	15 500	0.185	39 000	3190	2 570 000
Average…..	7.5	240	115.5	15 400	14 800	0.180	40 000	3410	2 510 000
$1:2\frac{1}{2}:3\frac{1}{2}$ … $\frac{W}{C} = 1.25$.	7.2	237	115.1	15 400	14 700	0.193	39 900	2590	2 200 000
	6.6	222	114.4	15 400	14 500	0.199	38 100	2730	2 130 000
	7.4	225	114.4	15 000	14 400	0.199	39 600	2540	2 360 000
Average…..	7.1	228	114.6	15 300	14 500	0.197	39 200	2620	2 230000
CONCRETE MADE WITH NATURAL SAND AND LIMESTONE									
$1:1\frac{3}{4}:2\frac{1}{4}$ … $\frac{W}{C} = 0.90$.	7.3	218	145.0	16 300	15 300	0.157	37 500	4720	3 420 000
	8.5	229	144.7	15 500	14 600	0.164	36 600	4720	3 720 000
	7.3	220	145.1	16 600	15 700	0.151	36 600	5040	3 630 000
age…..	7.7	222	144.9	16 100	15 200	0.157	36 900	4830	3 590 000
$1:2:3$ ….. $\frac{W}{C} = 1.00$.	6.4	210	143.9	16 200	15 200	0.163	40 200	3710	3 080 000
	5.1	197	144.2	15 700	14 800	0.152	42 600	4100	3 710 000
	4.0	200	145.5	15 600	14 900	0.152	35 100	3890	3 740 000
Average…..	5.2	202	144.5	15 800	15 000	0.156	39 300	3900	3 510 000
$1:2\frac{1}{2}:3\frac{1}{2}$ … $\frac{W}{C} = 1.20$.	5.6	208	146.6	16 100	14 600	0.184	37 800	2900	3 240 000
	7.0	222	145.8	15 500	15 000	0.175	36 600	2890	3 120 000
	6.6	205	145.6	16 800	15 600	0.163	40 200	3190	3 700 000
Average…..	6.4	212	146.0	16 100	15 100	0.174	38 200	2990	3 350 000

[a] Includes weight of beam.

TABLE V.—(*Continued.*)

Mix and Water-Cement Ratio	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	28-Day Tests, Beam				28-Day Tests, 6 by 12-in. Cylinders	
				Ultimate Load,[a] lb.	Load[a] at Yield Point, lb.	Deflection at Load of 13,000 lb., in.	Measured f_s at Yield Point, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.
CONCRETE MADE WITH FINE AND COARSE HAYDITE AGGREGATES[b]									
$1:1\frac{3}{4}:2\frac{1}{4}$... $W/C=1.97$	9.0	300	100.0	16 300	13 800	0.208	34 800	3310	1 730 000
	8.6	300	100.5	18 700	14 600	0.192	35 400	3200	1 580 000
Average.....	8.8	300	100.2	17 500	14 200	0.200	35 100	3250	1 650 000
$1:2:3$..... $W/C=1.10$	8.4	300	97.4	15 200	13 400	0.217	39 600	2400	1 290 000
	7.6	294	98.2	17 700	14 700	0.202	39 600	2380	1 460 000
Average.....	8.0	297	97.8	16 400	14 000	0.210	39 600	2390	1 370 000
$1:2\frac{1}{2}:3\frac{1}{2}$... $W/C=1.31$	7.1	270	96.4	15 400	14 700	0.223	41 400	1690	1 390 000
	7.8	269	96.9	15 100	14 700	0.218	41 400	1780	1 440 000
Average.....	7.5	270	96.6	15 200	14 700	0.220	41 400	1740	1 410 000

[a] Includes weight of beam.
[b] Made with lot 2 of cement, all others of lot 1.

Cement:

Universal portland cement was used in the tests. Two lots were used, all of the test specimens except a few to be noted later being made from the first lot. Average tensile strengths of 1:3 standard Ottawa mortar briquets are as follows:

	LOT 1	LOT 2
Tensile Strength, 7 days, lb. per sq. in..............	258	290
Tensile Strength, 28 days, lb. per sq. in.............	370	392

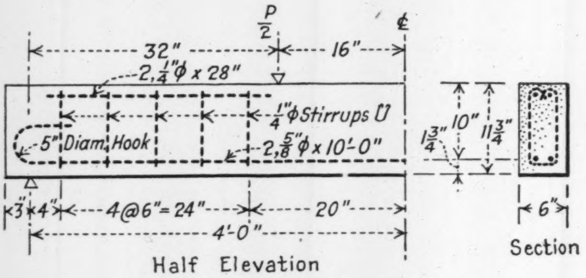
Reinforcing Steel:

Properties of the reinforcing steel used are given in Table IV.

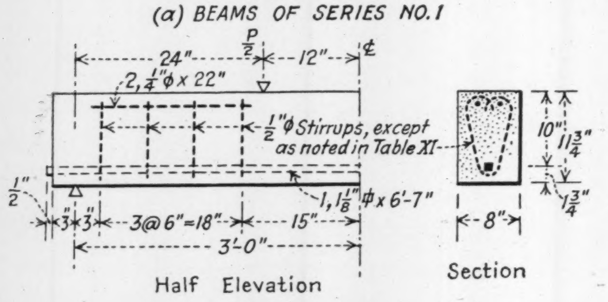
BEAM TESTS—WORKABILITY AND STRENGTH

An initial series of tests was made on beams and cylinders of machine-mixed concrete to secure information on mixes suitable for ordinary reinforced-concrete construction, with particular attention given to securing workability, surface finish and freedom from segregation. The selection of proportions of mix, consistency and method of mixing and placing was done with a view to producing light-weight concrete in a considerable range of strengths and to placing it easily in the forms and around reinforcing steel. Thirty-two beams, 6 by 12-in. in section, 8 ft. 6 in. long, were tested on an 8-ft. span with one-third point loading.

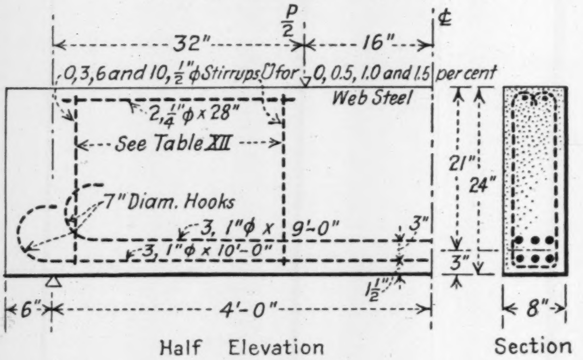
Experience had shown a considerable saving over the weight of ordinary concrete through the use of coarse Haydite and natural sand,


P/2
℄
32"
16"
2, 1/4"φ x 28"
1/4"φ Stirrups U
5" Diam. Hook
2, 5/8"φ x 10'-0"
1 3/4"
10"
11 3/4"
3"
4"
4@6"=24"
20"
4'-0"
6"
Half Elevation
Section

(a) BEAMS OF SERIES NO. 1


P/2
℄
24"
12"
2, 1/4"φ x 22"
1/2"φ Stirrups, except as noted in Table XI
1, 1 1/8"φ x 6'-7"
1/2"
3"
3"
3@6"=18"
15"
3'-0"
10"
11 3/4"
1 3/4"
8"
Half Elevation
Section

(b) BOND BEAMS OF SERIES B.B.


P/2
℄
32"
16"
0, 3, 6 and 10, 1/2"φ Stirrups U for 0, 0.5, 1.0 and 1.5 per cent Web Steel
2, 1/4"φ x 28"
See Table XII
7" Diam. Hooks
3, 1"φ x 9'-0"
3, 1"φ x 10'-0"
3"
1 1/2"
21"
24"
3"
6"
4'-0"
8"
Half Elevation
Section

(c) DIAGONAL TENSION BEAMS OF SERIES D.T.

FIG. 2.—Types of Test Beams.

at the same time avoiding the harshness found with some mixes containing fine Haydite. In the tests, therefore, both "sand and coarse Haydite" and "all-Haydite" mixes were used. The beams of this series consisted of three groups made with torpedo sand, using as coarse aggregates gravel, limestone and "C" Haydite of comparable size and gradation, and a fourth group made with Haydite fine and coarse aggregates. Data of the aggregates are given in Tables I and II.

Details of the test beams are shown in Fig. 2 (*a*). These beams were designed to fail in tension and did so without exception.

TABLE VI.—TESTS OF GRAVEL CONCRETE, SERIES G-2.

Aggregates used: Sand, S-2; gravel, G-2. See Tables I and II.
Water allowed for absorption, sand and gravel, 1 per cent by weight.
Proportions by loose dry volume; dry aggregates used.
Quantities required per cubic yard of concrete based on fresh concrete.
No allowance has been made for settlement and waste.
All values given are the average of 3 tests.

Mix	Water-Cement Ratio, by Volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	7-Day Cylinders		28-Day Cylinders		Quantities Required per Cubic Yard of Concrete		
					Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Cement, bbl.	Sand, cu. yd.	Gravel, cu. yd.
$1:1\frac{1}{2}:2\frac{1}{2}$	0.7	4.0	186	148.3	3680	3 460 000	5400	4 310 000	1.85	0.41	0.69
	0.8	9.1	230	148.3	2600	3 260 000	4020	3 850 000	1.83	0.41	0.68
	0.9	8.9	300	146.2	2020	2 660 000	3580	3 460 000	1.79	0.40	0.66
1:2:2...	0.7	3.4	190	147.6	3630	3 850 000	4600	4 140 000	1.83	0.54	0.54
	0.8	8.4	231	147.6	2770	3 170 000	4420	3 890 000	1.81	0.53	0.53
	0.9	9.9	300	148.1	2140	3 150 000	3580	3 710 000	1.79	0.53	0.53
$1:2\frac{1}{2}:1\frac{1}{2}$	0.7	1.2	157	145.9	3410	3 620 000	4480	4 000 000	1.79	0.66	0.40
	0.8	6.0	216	144.3	2860	3 170 000	4410	3 770 000	1.75	0.65	0.39
	0.9	8.6	236	143.8	2120	2 840 000	3590	3 430 000	1.72	0.64	0.38
1:2:3...	0.8	3.0	180	148.1	2880	3 430 000	4390	4 060 000	1.54	0.46	0.68
	0.9	8.0	230	147.3	2170	3 320 000	3790	3 720 000	1.52	0.45	0.68
	1.0	9.2	269	146.3	1660	2 310 000	3090	3 330 000	1.50	0.44	0.66
$1:2\frac{1}{2}:2\frac{1}{2}$	0.8	1.4	175	147.4	2740	3 290 000	3990	3 950 000	1.52	0.56	0.56
	0.9	7.3	230	146.8	2220	2 500 000	3830	4 030 000	1.50	0.56	0.56
	1.0	9.1	251	146.6	1730	2 330 000	3190	3 440 000	1.49	0.55	0.55
1:3:2...	0.9	3.4	195	145.3	2200	2 860 000	3740	3 750 000	1.47	0.65	0.44
	1.0	7.9	240	144.5	1850	2 690 000	3390	3 500 000	1.45	0.65	0.43
	1.1	8.2	255	143.7	1420	2 190 000	2770	2 970 000	1.43	0.64	0.42
$1:2\frac{1}{2}:3\frac{1}{2}$	1.0	4.2	213	147.3	1860	2 890 000	3080	3 800 000	1.31	0.48	0.68
	1.1	5.5	223	147.4	1290	2 360 000	2740	3 460 000	1.30	0.48	0.67
	1.2	7.5	245	144.3	1090	1 900 000	2290	3 140 000	1.26	0.47	0.65
1:3:3...	1.0	2.9	192	147.7	1840	2 890 000	3190	3 650 000	1.30	0.58	0.58
	1.1	5.7	222	144.7	1390	2 530 000	2710	3 530 000	1.26	0.56	0.56
	1.2	8.0	250	145.3	1100	1 850 000	2210	2 900 000	1.26	0.56	0.56
$1:3\frac{1}{2}:2\frac{1}{2}$	1.1	3.4	226	143.7	1430	2 360 000	2570	3 160 000	1.25	0.65	0.46
	1.2	7.7	251	144.0	1210	2 450 000	2160	2 880 000	1.24	0.64	0.46
	1.3	8.0	260	142.8	990	1 920 000	2020	2 970 000	1.22	0.63	0.45

The principal data of the concrete mixtures and of the tests of Series 1 are given in Table V. Three proportions of concrete were used, $1:1\frac{3}{4}:2\frac{1}{4}$, $1:2:3$ and $1:2\frac{1}{2}:3\frac{1}{2}$ by loose volume, the sand being 40 to 44 per cent of the total aggregate. Mixing was done in a "Wonder" batch mixer, and the concrete was placed in the form with shovels and spaded uniformly. Very good concrete surfaces were found when the forms were stripped. The beams and control cylinders were cured in a moist room and tested at the age of 28 days.

The slump[1] and flow[2] tests were made in accordance with the standard methods of test of the Society, fifteen ½-in. drops being used in the flow test. The deflection of the beam at midspan was read by use of Ames dials; the deflection at a load of 13,000 lb. is given in Table V as an index of the relative stiffness of the beams. The steel

TABLE VII.—TESTS OF SAND AND COARSE HAYDITE CONCRETE, SERIES S.

Aggregates used: Sand, S-2; coarse Haydite, C-6. See Tables I and II.
Proportions by loose dry volume.
Dry aggregates used.
Water allowed for absorption: Sand, 1 per cent; coarse Haydite, 7 per cent.
Quantities required per cubic yard of concrete based on fresh concrete.
No allowance has been made for settlement and waste.
All values given are the average of 3 tests.

Mix	Water-Cement Ratio, by Volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	7-Day Cylinders		28-Day Cylinders		Quantities Required per Cubic Yard of Concrete		
					Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Cement, bbl.	Sand, cu. yd.	Coarse Haydite C-6, cu. yd.
1:1½:2½	0.77	6.2	218	114.6	2700	2 120 000	4300	2 610 000	1.83	0.41	0.68
	0.87	8.7	252	113.6	2150	1 760 000	3810	2 440 000	1.79	0.40	0.66
	0.97	9.7	300+	112.7	1430	1 780 000	2940	2 370 000	1.75	0.39	0.65
1:2:2...	0.76	3.1	195	121.2	2820	2 520 000	4370	3 010 000	1.81	0.54	0.54
	0.86	8.5	243	120.5	2310	2 090 000	3960	2 780 000	1.78	0.53	0.53
	0.96	10.2	300	119.0	1660	1 930 000	3190	2 600 000	1.73	0.51	0.51
1:2½:1½	0.74	1.8	170	126.2	2810	2 460 000	4150	3 040 000	1.77	0.66	0.39
	0.84	6.1	220	125.3	2470	2 330 000	4030	3 020 000	1.74	0.64	0.39
	0.94	9.7	265	124.8	1890	2 050 000	3430	2 660 000	1.71	0.63	0.38
1:2:3...	0.89	4.6	220	113.3	1950	2 030 000	3640	2 600 000	1.51	0.45	0.67
	0.99	8.3	258	113.9	1500	1 730 000	3110	2 370 000	1.50	0.44	0.67
	1.09	8.6	270	113.0	1170	1 600 000	2530	2 150 000	1.47	0.44	0.65
1:2½:2½	0.87	2.6	194	119.0	2110	2 250 000	3490	2 680 000	1.50	0.56	0.56
	0.97	7.8	240	118.5	1610	1 780 000	3030	2 530 000	1.48	0.55	0.55
	1.07	8.5	275	116.3	1290	1 780 000	2700	2 310 000	1.43	0.53	0.53
1:3:2...	0.96	3.7	212	122.3	1710	2 070 000	3190	2 670 000	1.44	0.64	0.43
	1.06	6.9	230	123.0	1370	1 850 000	2590	2 470 000	1.44	0.64	0.43
	1.16	8.9	272	121.7	1150	1 710 000	2360	2 320 000	1.41	0.63	0.42
1:2½:3½	1.10	4.6	225	113.9	1240	1 480 000	2530	2 250 000	1.29	0.48	0.67
	1.20	6.2	238	112.0	950	1 320 000	2050	2 210 000	1.26	0.46	0.65
	1.30	7.6	246	112.3	800	1 070 000	1850	2 000 000	1.24	0.46	0.64
1:3:3...	1.09	3.1	210	117.5	1300	1 690 000	2620	2 450 000	1.27	0.56	0.56
	1.19	5.1	232	117.4	980	1 470 000	2100	2 220 000	1.25	0.56	0.56
	1.29	6.9	248	117.2	920	1 410 000	1920	2 250 000	1.24	0.55	0.55
1:3½:2½	1.17	3.1	216	120.8	1100	1 540 000	2180	2 470 000	1.24	0.64	0.46
	1.27	5.6	243	120.8	890	1 270 000	1880	2 320 000	1.22	0.63	0.45
	1.37	8.1	257	121.2	770	1 410 000	1440	2 210 000	1.21	0.63	0.45

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[1] Tentative Method of Test for Consistency of Portland-Cement Concrete (D 138 – 26 T), *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part I, p. 874 (1926); also 1929 Book of A.S.T.M. Tentative Standards, p. 474.

[2] Standard Methods of Making Compression Tests of Concrete (C 39 – 27), see 1927 Book of A.S.T.M. Standards, Part II, p. 112.

stress, f_s, was computed from the measured strains at midspan, using a modulus of elasticity for steel of 30,000,000 lb. per sq. in. The first strain measurements were taken at a load of 1000 lb. plus the weight of the beam; the measured steel stresses do not include the effect of this initial load:

TABLE VIII.—TESTS OF HAYDITE CONCRETE, SERIES A-3.

Aggregates used: Fine Haydite, A-3; coarse Haydite, C-6. See Tables I and II.
Proportions by loose dry volume.
Dry aggregates used.
Water allowed for absorption: fine, 14 per cent of dry weight; coarse, 7 per cent of dry weight.
Quantities required per cubic yard of concrete based on fresh concrete.
No allowance has been made for settlement and waste.
All values given are the average of 3 tests.

Mix	Water-Cement, Ratio, by Volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	7-Day Cylinders		28-Day Cylinders		Quantities Required per Cubic Yard of Concrete		
					Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Cement, bbl.	Fine Haydite A-3, cu. yd.	Coarse Haydite C-6, cu. yd.
1:1½:2½	0.86	5.4	232	99.0	1990	1 640 000	3700	2 010 000	1.86	0.41	0.69
	0.96	6.6	251	96.8	1500	1 500 000	3060	1 860 000	1.79	0.40	0.66
	1.06	9.6	300	96.3	1160	1 210 000	2440	1 800 000	1.75	0.39	0.65
1:2:2...	0.88	5.5	230	99.5	1880	1 600 000	3470	1 950 000	1.83	0.54	0.54
	0.98	7.5	249	97.6	1460	1 480 000	2890	1 670 000	1.77	0.52	0.52
	1.08	9.9	300	97.1	1210	1 320 000	2490	1 770 000	1.73	0.51	0.51
1:2½:1½	0.90	3.1	192	99.6	1850	1 530 000	3320	1 890 000	1.79	0.66	0.40
	1.00	6.6	251	98.6	1470	1 400 000	2770	1 840 000	1.75	0.65	0.39
	1.10	9.7	300	97.7	1060	1 300 000	2150	1 660 000	1.70	0.63	0.38
1:2:3...	1.01	1.9	175	95.9	1370	1 410 000	2530	1 820 000	1.53	0.45	0.68
	1.11	5.3	240	95.1	1160	1 300 000	2300	1 730 000	1.50	0.44	0.67
	1.21	8.4	300	94.8	870	1 410 000	1920	1 670 000	1.47	0.44	0.65
1:2½:2½	1.03	1.7	187	96.2	1250	1 490 000	2620	1 850 000	1.51	0.56	0.56
	1.13	5.4	240	96.9	1070	1 160 000	2310	1 810 000	1.50	0.56	0.56
	1.23	7.7	285	95.7	900	1 200 000	2060	1 630 000	1.46	0.54	0.54
1:3:2...	1.14	3.0	230	97.1	1120	1 230 000	2350	1 770 000	1.47	0.66	0.44
	1.24	7.2	272	96.0	870	1 140 000	1960	1 660 000	1.44	0.64	0.43
	1.34	8.2	300+	94.8	670	1 030 000	1310	1 450 000	1.40	0.62	0.42
1:2½:3½	1.25	1.0	187	95.0	750	1 240 000	1580	1 330 000	1.30	0.48	0.68
	1.35	7.4	250	94.7	760	1 190 000	1680	1 620 000	1.28	0.48	0.67
	1.45	7.6	288	92.6	540	1 000 000	1310	1 540 000	1.24	0.46	0.64
1:3:3...	1.27	2.7	200	95.2	820	1 320 000	1760	1 690 000	1.29	0.57	0.57
	1.37	5.3	243	95.8	710	1 080 000	1620	1 310 000	1.28	0.57	0.57
	1.47	6.7	298	93.0	540	970 000	1280	1 570 000	1.23	0.55	0.55
1:3½:2½	1.39	2.7	218	95.7	640	970 000	1470	1 550 000	1.26	0.65	0.47
	1.49	3.3	232	94.7	560	1 020 000	1220	1 630 000	1.23	0.64	0.46
	1.59	6.9	297	93.9	470	840 000	1110	1 320 000	1.21	0.62	0.46

It was first intended to make the four groups of beams of Table V of concretes having the same net water-cement ratios. However, it was found that the absorption allowances arrived at by direct tests of Haydite aggregates were not sufficient to give equal workability with the gravel and limestone aggregates. This may have been due to differences in gradation and surface texture of the different materials. The total quantities of mixing water were chosen, therefore, so as to bring all mixes to approximately equal workabilities, as indicated by slump tests.

Since all of the beams failed by tension in the horizontal steel, there should be little difference in the maximum loads, except as the arm of the resisting couple, *jd*, might vary with the elastic properties of the different concretes. The relatively low value of the modulus of elasticity for the Haydite concretes tends to decrease the value of *jd* slightly; however, the ultimate loads on the beams made with sand and coarse Haydite are seen to be only 3 to 4 per cent less than those for the beams of gravel and limestone concrete.

TABLE IX.—TESTS OF HAYDITE CONCRETE, SERIES A-2.

Aggregates used: Fine Haydite, A-2; coarse Haydite, C-6. See Tables I and II.
Moisture present in aggregates when used: C-6, 6 per cent; A-2, 27 per cent of dry weight.
Water allowed for absorption: A-2 supplied 7 per cent of dry weight as free water; C-6 required 3 per cent of dry weight additional water.
Proportions by loose moist volumes.
Quantities required per cubic yard of concrete based on fresh concrete.
No allowance has been made for settlement and waste.
All values given are the average of 3 tests.

Mix	Water-Cement Ratio, by Volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	7-Day Cylinders		28-Day Cylinders		Quantities Required per Cubic Yard of Concrete		
					Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Cement, bbl.	Fine Haydite A-2, cu. yd.	Coarse Haydite C-6, cu. yd.
1:1½:2½	0.77	3.0	182	104.9	2850	1 940 000	4510	2 070 000	2.12	0.47	0.79
	0.87	6.5	243	103.3	2230	1 690 000	3690	2 020 000	2.05	0.46	0.76
	0.97	9.5	290	99.8	1340	1 190 000	2710	1 790 000	1.95	0.43	0.72
1:2:2...	0.77	2.3	170	105.8	3180	2 020 000	4550	2 110 000	2.15	0.64	0.64
	0.87	8.3	243	105.1	2410	1 660 000	4050	2 050 000	2.09	0.62	0.62
	0.97	10.0	300	101.5	1490	1 400 000	2870	1 900 000	1.98	0.59	0.59
1:2½:1½	0.78	1.2	146	106.3	3240	1 900 000	4810	2 220 000	2.16	0.80	0.48
	0.88	8.1	220	106.2	2660	1 680 000	4550	2 180 000	2.11	0.78	0.47
	0.98	10.5	300	103.6	1460	1 370 000	2990	1 770 000	2.02	0.75	0.45
1:2:3...	0.89	1.4	144	101.9	2150	1 680 000	3690	1 970 000	1.76	0.52	0.78
	0.99	2.5	192	101.5	1670	1 540 000	3250	1 920 000	1.73	0.51	0.77
	1.09	7.5	235	100.1	1350	1 390 000	2820	1 780 000	1.68	0.50	0.75
1:2½:2½	0.90	1.3	145	102.8	2320	1 670 000	3780	2 010 000	1.79	0.66	0.66
	1.00	3.5	193	102.9	1900	1 640 000	3600	2 080 000	1.76	0.65	0.65
	1.10	7.2	240	101.1	1590	1 590 000	3060	1 910 000	1.70	0.63	0.63
1:3:2...	1.00	2.8	201	103.8	1810	1 550 000	3330	1 940 000	1.78	0.79	0.53
	1.10	6.5	229	103.0	1600	1 690 000	3130	1 780 000	1.70	0.76	0.51
	1.20	8.6	292	102.3	1220	1 430 000	2430	1 620 000	1.70	0.75	0.51
1:2½:3½	1.10	1.4	175	98.9	1360	1 330 000	2620	1 880 000	1.48	0.55	0.77
	1.20	5.2	215	99.3	1000	1 320 000	2040	1 660 000	1.47	0.55	0.76
	1.30	7.7	280	99.1	800	1 140 000	1790	1 550 000	1.45	0.54	0.75
1:3:3...	1.11	1.5	160	100.7	1460	1 500 000	2880	1 910 000	1.51	0.67	0.67
	1.21	5.0	220	99.2	1090	1 260 000	2270	1 780 000	1.47	0.65	0.65
	1.31	7.0	270	99.8	1040	1 200 000	1970	1 590 000	1.46	0.65	0.65
1:3½:2½	1.22	4.0	207	99.8	1150	1 370 000	2450	1 810 000	1.48	0.77	0.55
	1.32	7.7	273	100.2	900	1 030 000	1890	1 690 000	1.46	0.76	0.54
	1.42	8.8	293	100.9	860	1 090 000	1770	1 520 000	1.46	0.76	0.54

COMPRESSION TESTS OF HAYDITE CONCRETES

To supplement and extend the data of the beam tests of the preceding section, several series of compression tests of 6 by 12-in. machine-mixed concrete cylinders were made. In addition to compressive strengths, other properties of the mixtures were found, such as workability, unit weight, yield, and modulus of elasticity. Four principal series of tests were made as follows:

Series G-2.—This series consisted of 162 cylinders, made with sand and gravel aggregates, for comparison with series S and A-3. Nine proportions of mix and three consistencies were used. Three cylinders of a kind were tested at ages of 7 and 28 days. The proportions were determined by the use of loose, dry volumes. Test data are given in Table VI.

Series S.—This series was identical with Series G-2 except that the aggregates were natural sand and coarse Haydite. Test data are given in Table VII.

Series A-3.—This series was also identical with Series G-2 except that the aggregates were fine and coarse Haydite. Test data are given in Table VIII.

Series A-2.—This series was made with fine and coarse Haydite aggregates. While the preceding three series were proportioned by loose, dry volume, this series was proportioned by loose, moist volumes. The fine aggregate carried about 27 per cent of total moisture; the coarse, 6 per cent. Since the aggregates were bulked considerably, the mixes of this series had a considerably higher cement content than the corresponding mixes of the previous three series. Series A-3 and A-2 furnish an extreme range in moisture conditions, the first using oven-dried aggregates and the second a supply of aggregate with an unusually high moisture content. The test data of Series A-2 are given in Table IX.

Tables VI to IX contain information as to the effect of various mixes, consistencies and proportions of fine and coarse aggregate upon the strength, unit weight and modulus of elasticity. The quantities of materials required per cubic yard of the different mixes as determined from measurements of yield are also given. It is seen that the quantities in Tables VI, VII and VIII, for loose, dry proportions, are practically alike for the three kinds of concrete; the mixes of Table IX, based on loose, moist volumes, have much higher cement requirements.

EFFECT OF AGE ON COMPRESSIVE STRENGTH

In connection with the beam tests of Series 1, two groups of cylinders were made to study the increase in compressive strength at ages of 7 and 28 days, 3, 6 and 12 months. These cylinders were of a 1:2:3 mixture corresponding to that of the beams of Table V. One group was made with sand and gravel; the other with sand and coarse Haydite "C." The aggregates were proportioned by loose volume, the sand being dry and the Haydite containing about 6 per cent of moisture.

TABLE X.—EFFECT OF AGE ON COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY.

All cylinders moist cured, tested moist.
Aggregates used: Series 1: Sand, S-1; gravel, G-1; coarse Haydite, C-6. Series T: Sand, S-2; fine Haydite, A-3; coarse Haydite, C-6. See Tables I and II.
Wet consistencies, 6 to 9-in. slumps.
All values given represent the average of 3 tests.

Age at Time of Test	Series 1		Series T		
	Sand and Gravel, 1:2:3 Mix, Water-Cement Ratio, 1.00	Sand and Coarse Haydite, 1:2:3 Mix, Water-Cement Ratio, 1.05	Fine and Coarse Haydites, $1:1\frac{1}{4}:1\frac{3}{4}$ Mix, Water-Cement Ratio, 0.66	Moist Coarse Haydite and Sand, $1:1\frac{3}{4}:2\frac{1}{4}$ Mix, Water-Cement Ratio, 0.99	Dry Coarse Haydite and Sand, $1:1\frac{3}{4}:2\frac{1}{4}$ Mix, Water-Cement Ratio, 1.02
COMPRESSIVE STRENGTH OF 6 BY 12-IN. CYLINDERS, LB. PER SQ. IN.					
7 Days	2430	1650	3350	2160	1920
14 Days	....	....	4350	2990	2920
28 Days	3980	3450	5120	3870	3770
3 Months	4670	4500	5680	4850	4640
6 Months	4730	4590	6800	4870	5180
12 Months	5700	5070	....	....	....
COMPRESSIVE STRENGTH IN TERMS OF 28-DAY STRENGTHS, PER CENT					
7 Days	61	48	65	56	51
14 Days	....	....	85	77	78
28 Days	100	100	100	100	100
3 Months	118	130	111	125	123
6 Months	119	133	133	126	137
12 Months	145	147	....	....	....
INITIAL MODULUS OF ELASTICITY, LB. PER SQ. IN.					
7 Days	2 970 000	1 830 000	2 010 000	2 120 000	1 900 000
14 Days	....	....	2 100 000	2 190 000	2 440 000
28 Days	3 910 000	2 480 000	2 180 000	2 680 000	2 660 000
3 Months	4 500 000	2 710 000	2 270 000	2 890 000	2 850 000
6 Months	4 660 000	2 590 000	2 630 000	2 920 000	3 020 000
12 Months	4 900 000	2 790 000	....	....	....
UNIT WEIGHT OF FRESH CONCRETE, LB. PER CU. FT.					
	147.4	115.4	102.1	116.3	116.3

Three later groups of cylinders, Series T, were made with richer mixes, using oven-dried Haydite aggregates. One group was made

TABLE XI.—DATA OF BOND TESTS, SERIES B.B.

Aggregates used: Sand, S-2; gravel, G-2; fine Haydite, A-3; coarse Haydite, C-6 used with natural sand, C-3 used with fine Haydite. See Tables I and II.
Age of specimens, 28 days ±1 day.
Nominal $j = \frac{7}{8}$ assumed for all beams.
All specimens moist cured.
Proportions by loose dry volume.
Dry aggregates used. Water allowed for absorption: Sand and gravel, 1 per cent; fine Haydite, 14 per cent; coarse Haydite, 7 per cent.

Mix and Water-Cement Ratio, by volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	Beam Tests			Pull-Out Tests		6 by 12-in. Cylinders (Average of 3)	
				Load[a] at End Slip of 0.001 in., lb.	Ultimate Load,[a] lb.	Average Bond Stress at Ultimate Load, lb. per sq. in.	Average Bond Stress		Compressive Strength, lb. per sq. in.	Initial Modulus of Elasticity, lb. per sq. in.
							At End Slip of 0.001 in., lb. per sq. in.	At Ultimate Load, lb. per sq. in.		
CONCRETE MADE WITH NATURAL SAND AND GRAVEL AGGREGATES										
$1:1\frac{3}{4}:2\frac{1}{4}$. $\frac{W}{C} = 0.80$ …	8.6	250	147.7	19 700	28 400	358	445	620	4040	3 780 000
	8.5	250	146.9	27 500	28 100	355	528 397	700 577	3960	3 730 000
Average.......	8.5	250	147.3	23 600	28 300	357	457	633	4000	3 750 000
$1:2\frac{1}{4}:2\frac{3}{4}$. $\frac{W}{C} = 0.90$ …	7.7	242	145.7	20 500	25 400	320	494	633	3180	3 660 000
	7.8	245	146.1	24 200	26 600	336	480 517	583 578	3410	3 640 000
Average.......	7.7	244	145.9	22 300	26 000	328	497	598	3300	3 650 000
$1:2\frac{3}{4}:3\frac{1}{4}$. $\frac{W}{C} = 1.10$ …	7.0	251	145.7	24 400	26 200	330	458	530	2990	3 250 000
	7.8	244	146.6	22 000	25 200[b]	317	483 525	525 616	2720	3 380 000
Average.......	7.4	247	146.1	23 200	25 700	324	489	557	2860	3 310 000
CONCRETE MADE WITH NATURAL SAND AND COARSE HAYDITE										
$1:1\frac{3}{4}:2\frac{1}{4}$. $\frac{W}{C} = 0.87$ …	7.3	243	119.4	21 800	24 500	309	436	625	3970	2 670 000
	7.8	243	117.1	21 900	24 800	313	431 447	575 567	3880	2 500 000
Average.......	7.5	243	118.3	21 800	24 700	311	438	589	3930	2 580 000
$1:2\frac{1}{4}:2\frac{3}{4}$. $\frac{W}{C} = 0.98$ …	7.4	250	119.6	22 500	26 300	333	405	505	3390	2 500 000
	7.5	261	118.4	22 300	24 500	309	319 442	461 605	3400	2 450 000
Average.......	7.5	255	119.0	22 400	25 400	321	389	524	3400	2 470 000
$1:2\frac{3}{4}:3\frac{1}{4}$. $\frac{W}{C}$ =|1 19 …	7.3	274	118.5	24 500	28 900[b]	365	389	466	2560	2 250 000
	7.0	260	117.9	19 500	21 800	275	422 367	519 458	2520	2 160 000
Average.......	7.1	267	118.2	22 000	25 400	320	393	481	2540	2 200 000
CONCRETE MADE WITH FINE AND COARSE HAYDITE AGGREGATES										
$1:1\frac{3}{4}:2\frac{1}{4}$. $\frac{W}{C} = 0.97$ …	6.2	253	97.9	18 100	20 400	258	241	403	2820	1 880 000
	5.4	247	97.9	18 300	22 400	283	308 292	500 427	2910	1 990 000
Average.......	5.8	250	97.9	18 200	21 400	270	280	443	2860	1 930 000
$1:2\frac{1}{4}:2\frac{3}{4}$. $\frac{W}{C} = 1.12$ …	3.6	233	95.4	16 500	19 200	243	356	497	2580	1 760 000
	8.0	287	92.6	20 200	22 700	287	367 381	472 530	2250	1 630 000
Average.......	5.8	260	94.0	18 300	21 000	265	368	483	2420	1 690 000
$1:2\frac{3}{4}:3\frac{1}{4}$. $\frac{W}{C} = 1.36$ …	6.6	265	94.6	15 900	18 400[b]	233	280	405	1760	1 490 000
	5.2	252	93.9	14 400	20 600[b]	260	286 319	422 472	1720	1 640 000
Average.......	5.9	258	94.3	15 100	19 500	247	295	433	1740	1 560 000

[a] Including weight of beam.

[b] Stirrups in these beams were $\frac{1}{2}$-in. square instead of round. No effect on failure of beam.

with fine and coarse Haydite to which a definite amount of moisture had been added one day previous to the time of mixing. Of the other two groups, one used coarse Haydite to which a definite moisture content had been added and the other used the dried Haydite directly. These three groups of cylinders provided for test at ages of 7, 14 and 28 days, 3 and 6 months, 1, 2 and 5 years.

All specimens were cured in the moist room until test, and were tested moist. Table X gives values of the strengths of the five lots of cylinders at ages up to 6 months, as well as values of the initial modulus of elasticity and of the unit weight of each kind of concrete as freshly placed. The table also shows the strengths at different ages expressed as ratios of the standard 28-day strength. It appears from Table X that the increase in strength of the four Haydite concretes compares very well with that of the sand and gravel concrete. The strengths of the two lots of Series 1 may be compared even though they have somewhat different water-cement ratios. It is seen that although the Haydite concrete had less strength at the earlier ages, it had almost equaled the strength of the gravel concrete at the ages of 3 and 6 months.

BOND TESTS

To furnish data for the design of reinforced-concrete members, bond and diagonal tension tests were made. In the bond series, designated B.B., 18 beams and 27 pull-out specimens were tested, together with 54 6 by 12-in. companion cylinders. The details of the beams are shown in Fig. 2 (*b*). The pull-out specimen used consisted of a $1\frac{1}{8}$-in. square deformed bar, the same as those used in the beams, embedded axially in an 8 by 8-in. concrete cylinder. The bars used were deformed bars of rail steel, and had very gradually tapering diamond-shaped projections. Two beams and three pull-out specimens were made with three richnesses of mix and three combinations of aggregates, and tested when 28 days old. All specimens were moist cured. Strain measurements were taken on the beams and measurements of end slip of reinforcing bar were taken with attached 0.0001-in. Ames dials. The beams were tested in an inverted position to facilitate strain measurements. The principal data of the tests are given in Table XI. For comparative purposes the minor variations in the lever arm of the resisting couple, *jd*, due to different qualities of concrete, have been neglected and a value of *jd* of 8.75 in. has been used in the computations of the average bond stress, *u*, as found from the beam tests

Although the bars used were classed as deformed bars, the failure in the pull-out test was generally reached at a slip of about 0.01 in., when either the concrete block split or the bar merely continued to slip with a decrease in load, after the manner of a plain bar.

It is seen by reference to Table XI that the maximum nominal bond strength developed in the beam tests as calculated from the usual bond formula ranged from 8 to 14 per cent of the compressive strength of the companion cylinders, with the higher ratios generally corresponding to the leaner mixes.

The maximum bond strength developed in the pull-out tests varied from 15 to 25 per cent of the cylinder strength.

It is apparent that the relation of bond strength to compressive strength is essentially the same for Haydite concrete as for gravel concrete, so that design rules in which the working stress is given as a percentage of the compressive strength would apply equally well to both materials. It is to be noted, however, that the current rules permitting a working bond stress on deformed bars of 0.05 f'_c (f'_c is the compressive strength at 28 days), if applied to the test beams of the $1:1\frac{3}{4}:2\frac{1}{4}$ mix would result in a factor of safety as low as 1.8 for the gravel and sand concrete, 1.6 for the Haydite "C" and sand concrete and 1.9 for all-Haydite concrete. Considering the progressive nature of bond failure and the small factors of safety found for the richer mixtures, it appears that the choice of working stresses in bond, particularly for concrete of high strength, needs further careful study.

DIAGONAL TENSION TESTS

Twenty-four large beams, designed to fail by diagonal tension, were tested, Series D.T. Eighteen were of the mixes and proportions used in the bond tests and contained no web reinforcement, while the remaining six were of one proportion of sand and Haydite "C" concrete, with three different amounts of web reinforcement in the form of stirrups. Three companion 6 by 12-in. cylinders were made with each beam. Beams and cylinders were moist-cured together.

The details of the beams, which were 8 by 24-in. in section and of 8-ft. span, are shown in Fig. 2 (*c*). The beams were tested in an inverted position, with the load applied at the one-third points. To avoid tensile failure, 2.8 per cent of longitudinal steel were used. Web reinforcement of 0.5, 1.0 and 1.5 per cent was provided in the form of $\frac{1}{2}$-in. round U-stirrups at spacings of 10, 5, and $3\frac{1}{4}$ in. This steel had a yield point of 52,800 lb. per sq. in., which was higher than designed for originally. Strain measurements were taken on the concrete at midspan, on the longitudinal steel at midspan and near the ends, and on stirrups about midway between support and load point.

TABLE XII.—DATA OF DIAGONAL TENSION TESTS, SERIES D.T.

Aggregates used: Sand, S-3; gravel, G-3; fine Haydite, A-4; coarse Haydite, C-7. See Tables I and II.
Test beams, 8 by 24-in., 9 ft. long, moist cured 28 days.
Nominal value of $j = \frac{7}{8}$ assumed for all beams.
Proportions by loose dry volume.
Aggregates used moist. Total allowance for absorption: Sand and gravel, 1 per cent; fine Haydite, 18 per cent; coarse Haydite, 8 to 11 per cent.

Mix and Water-Cement Ratio, by Volume	Slump, in.	Flow	Unit Weight of Fresh Concrete, lb. per cu. ft.	Web Steel, per cent	Ultimate Load,[a] lb.	Shearing Stress at Ultimate Load, lb. per sq. in.	Computed f_s at Ultimate Load, lb. per sq. in.	6 by 12-in. Cylinders (Average of 3)	
								Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.
CONCRETE MADE WITH NATURAL SAND AND GRAVEL AGGREGATES									
$1:1\frac{3}{4}:2\frac{1}{4}$	6.0	213	147.7	0	142 900	484	26 100	4760	3 800 000
$W/C = 0.80$	7.0	242	148.7	0	159 700	540	29 200	4620	4 100 000
Average.......	6.5	227	148.2		151 300	512	27 600	4690	3 950 000
$1:2\frac{1}{4}:2\frac{3}{4}$	3.8	202	148.6	0	151 800	514	27 700	4290	3 830 000
$W/C = 0.90$	6.1	224	148.1	0	134 100	423	24 500	3860	3 570 000
Average.......	5.0	213	148.3		142 900	463	26 100	4050	3 700 000
$1:2\frac{3}{4}:3\frac{1}{4}$	8.0	276	146.4	0	105 800	357	19 300	2230	3 090 000
$W/C = 1.10$.	6.3	257	146.9	0	116 500	394	21 300	2630	3 180 000
Average.......	7.1	266	146.6		111 100	375	20 300	2430	3 130 000
CONCRETE MADE WITH NATURAL SAND AND COARSE HAYDITE									
$1:1\frac{3}{4}:2\frac{1}{4}$	7.6	240	119.9	0	132 900	450	24 300	4550	2 850 000
$W/C = 0.84$	7.7	255	119.1	0	133 700	453	24 500	3930	2 630 000
Average.......	7.6	247	119.5		133 300	451	24 400	4240	2 740 000
$1:2\frac{1}{4}:2\frac{3}{4}$	4.0	221	120.5	0	124 900	423	22 900	3730	2 510 000
$W/C = 0.94$.	7.0	253	121.0	0	124 900	423	22 900	3460	2 550 000
Average.......	5.5	237	120.7		124 900	423	22 900	3590	2 530 000
$1:2\frac{1}{4}:2\frac{3}{4}$	6.3	235	118.7	0.5	155 300	526	28 500	3480	2 500 000
$W/C = 0.92$	5.3	228	118.8	0.5	169 000	572	30 900	3870	2 520 000
Average.......	5.8	231	118.8	0.5	162 100	549	29 700	3670	2 510 000
$1:2\frac{1}{4}:2\frac{3}{4}$	6.6	242	119.0	1.0	191 000	644	34 800	3640	2 390 000
$W/C = 0.96$	6.8	260	119.2	1.0	201 200	682	36 800	3480	2 500 000
Average.......	6.7	251	119.1	1.0	196 100	663	35 800	3560	2 440 000
$1:2\frac{1}{4}:2\frac{3}{4}$	6.7	250	119.6	1.5	204 600	693	37 500	3550	2 500 000
$W/C = 0.96$	6.9	256	120.3	1.5	205 700	698	37 700	3400	2 330 000
Average.......	6.8	253	119.9	1.5	205 100	695	37 600	3470	2 410 000
$1:2\frac{3}{4}:3\frac{1}{4}$[b] ...	7.5	280	118.5	0	132 400	448	24 300	2420	1 930 000
$W/C = 1.17$[b]	4.0	231	120.6	0	142 500	482	26 100	3280	2 430 000
Average[b]	5.7	255	119.5		137 500	465	25 200	2850	2 180 000
CONCRETE MADE WITH FINE AND COARSE HAYDITE AGGREGATES									
$1:1\frac{3}{4}:2\frac{1}{4}$	7.1	257	102.0	0	95 500	324	17 500	3400	1 950 000
$W/C = 0.88$	8.5	266	102.3	0	98 400	333	18 000	3090	1 850 000
Average.......	7.8	261	102.1		96 900	328	17 700	3240	1 900 000
$1:2\frac{1}{4}:2\frac{3}{4}$	6.5	250	100.1	0	89 100	308	16 600	2450	1 740 000
$W/C = 0.98$	2.0	200	100.4	0	107 000	363	19 600	2990	1 650 000
Average.......	4.2	225	100.2		98 000	335	18 100	2720	1 690 000
$1:2\frac{3}{4}:3\frac{1}{4}$	5 6	235	99.9	0	86 100	291	16 700	1790	1 510 000
$W/C = 1.19$	4.6	213	99.5	0	67 200	227	12 300	1800	1 460 000
Average.......	5.1	224	99.7		76 600	259	14 500	1790	1 480 000

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[a] Including weight of the beam.

[b] Made with lot 2 of cement, all others of lot 1.

Table XII gives the essential results of the tests. For the beams without web reinforcement, those of gravel concrete developed a shearing unit stress, v, equal to 11 to 15 per cent of the compressive strength f'_c, of the 6 by 12-in. control cylinders. For the sand and Haydite concrete the ratio varied from 11 to 16 per cent, while for the all-Haydite concrete it varied from 10 to 14 per cent. These beams failed initially by diagonal tension.

Of the beams containing web reinforcement, those with 0.5 and 1.0 per cent failed by slip of longitudinal steel and crushing of concrete at the support; those with 1.5 per cent by tension in longitudinal steel followed by crushing of the concrete. From the loads carried and from the measured stirrup stresses it is evident that the strength of the web steel was not fully developed in any of these tests, so that the shearing stresses listed do not represent the full web resistance of the beams.

CONCLUSIONS

The investigation furnishes information regarding Haydite concrete that may be of general interest:

1. The average unit weights of the fine and coarse Haydite used were respectively 54 and 43 lb. per cu. ft. by dry, loose measure and 62 and 47 lb. per cu. ft. by standard dry, rodded measure.

2. Concrete was made with Haydite aggregates with no particular departure from ordinary methods. The same mixing procedure was used with Haydite concrete as with gravel and limestone concretes. With the consistencies used in Series 1, no difference was noted in the work required to place the concrete or in the appearance of the molded surfaces of beams made with gravel, limestone and coarse Haydite. The Haydite beams presented a harsher top surface, making finishing more difficult where no topping mortar was used.

3. The proportion of coarse aggregate that may be used depends upon its size, whether the material be Haydite, gravel or limestone. The gravel and limestone used in these tests were of nearly the same size as the "C" Haydite. The usable proportion of any of these aggregates was limited by the $\frac{3}{4}$-in. maximum size. The ease of working and placing of concrete is also very largely dependent upon the aggregate size, but it is evident that the gradation and texture of the Haydite aggregates required a somewhat greater water-cement ratio than gravel aggregates in similar mixes.

4. Because of the high water absorption by the Haydite, some difficulty was met in the choice of the proper allowance for absorption

in determining the water-cement ratio. The tests indicate that the absorption allowance for Haydite is not a fixed quantity but depends upon the initial moisture content of the aggregate as used. Thus the allowances found by tests of dry Haydite and used in Series A-3 are too small for the moist aggregates of Series A-2.

The absorption allowances used were those found by test for material immersed for one hour; for dry Haydites, 7 per cent for the coarse and 14 per cent for the fine; for initially moist Haydite, varying percentages depending upon the initial moisture content of the aggregates. Had three-hour absorptions been used, all of these values would have been higher by 1 per cent or more. Which of these amounts represents the actual condition in the concrete is debatable; it is clear that with such large absorption values, any error will have a large effect upon the water-cement ratio. It must be remembered that these percentages are based upon the dry weight of the light aggregates which are about one-half the weight of sand and gravel aggregates.

5. Concrete made with Haydite aggregates required greater water-cement ratios for the same mixes and equal slumps, and generally showed lower strengths than those with gravel aggregates. For equal water-cement ratios, however, the strengths of concretes made with sand and gravel, sand and coarse Haydite, and fine and coarse Haydite were very nearly equal. Any strength differences found may be explained as due to the effect of errors in absorption allowances upon the water-cement ratio. There is no indication that the strength of any of the mixtures was limited by the strength of the aggregate particles.

6. The modulus of elasticity of Haydite concrete is markedly lower than that of gravel and limestone concrete of like proportions. For the considerable range of mixes and consistencies included in Series G-2, S, and A-3 (Tables VI, VII and VIII) the values of initial modulus of elasticity for concretes made with coarse Haydite and natural sand are about 75 per cent and for concretes made with all-Haydite aggregates about 55 per cent of the values for sand and gravel concretes of the same strengths.

7. The weight per cubic foot of the Haydite concretes used varied from 93 to 106 lb. for all-Haydite concrete and from 112 to 126 lb. for concrete made with sand and coarse Haydite. The range in weights is due to variations in mixtures, in proportions of fine and coarse aggregates used, and to variations in moisture contents of aggregates when used.

8. The increase in compressive strength with age of moist stored

Haydite concrete compares well with that for gravel concrete for periods up to 6 months.

9. The ratio of bond resistance to compressive strength at the age of 28 days was essentially the same for like mixes of gravel and Haydite concrete.

10. For beams without web reinforcement, which failed by diagonal tension, the ratio of the shearing unit stress of the compressive strength of control cylinders was practically the same for corresponding mixtures of gravel and Haydite concrete.

DISCUSSION

MR. RALPH DOWNIE[1] (*presented in written form*).—Haydite concrete has been used for the decks of seven 240-ft. vertical lift highway bridges over the Welland Ship Canal; and is to be used for one more. We have, therefore, had some field experience in its use. Our supply of Haydite was from the plants at Kansas City, Mo., and Cooksville, Ont., Canada. The properties of these materials were very similar and were substantially the same as the material used by the authors. We consider all to have an excess of flour. No gravel or sand of similar grading would be accepted on this work.

The implication of the authors that concrete may be made with Haydite aggregates with no particular departure from ordinary methods is considered misleading. Good concrete can be, and is being, made with Haydite; but the engineer and contractor will find that this material has perversities of its own.

The wetting down of the stock pile, as recommended by the makers, will be found advantageous. The indeterminate amount of surface water introduced with the batch makes the measurement of water for the batch a matter of cut and try. The question of absorption will be discussed later. The 3-minute mix, beneficial to any concrete, is a necessity with Haydite. More cement will probably be required because aggregate of similar grading is unusual, and as a factor of safety, owing to the uncertainty of the amount of water. I consider that the true water-cement ratio may only be determined inferentially by comparing tests results with those of gravel or stone aggregates with the same cement.

Haydite and sand have not been used on this work. Combined Haydite and combined sand and gravel were used together to secure an intermediate weight in a bridge counterweight.

This might have been satisfactory in a highway type of concrete. In concrete with a 6-in. slump, for use in heavily reinforced work, an almost total segregation of the light and heavy materials resulted.

The discussion and conclusions on absorption clear up many points that have been troubling us here. Our determinations on the plain materials are in substantial agreement. Compression tests, however, compared with our water-cement ratio curve would indicate from 4 to 6 per cent absorption. Would this indicate that the cement took up more than the surface water from the aggregate? It must be stated here that our laboratory is a production, rather than a research organization, consequently our inference is based on a comparatively small number of laboratory tests.

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[1] Testing Engineer, Department of Railways and Canals, Welland Ship Canal, Thorold, Ont., Canada.

Unit weights of Haydite concrete are reported herewith in a progress report on the subject of Haydite, issued to the Engineer in Charge of the Welland Ship Canal. Field mixes are reported as follows: Cement in Canadian sacks (87½ lb. net), Haydite in cubic feet, wet and loose.

Cubic foot blocks for unit weight determination were made at the same time as the compression test specimens:

WELLAND SHIP CANAL TESTING LABORATORIES
Progress Report on Haydite

Bridge 5.—The average unit weight of the Haydite concrete was 93.2 lb. per cu. ft. The compression tests were as follows:

SPECIMEN	DATE SAMPLED	STRUCTURE	AVERAGE STRENGTH, 6 BY 12-IN. CYLINDERS, LB. PER SQ. IN. 28 DAY	3 MOS.	UNIT WEIGHT, LB. PER CU. FT.	APPROXIMATE FIELD MIX BY VOLUME
No. 12168–73	Aug. 13, 1929	Roadway E	1258	1979	94.3	2½:5:8
No. 12174–79	Aug. 13, 1929	Roadway W	1454	1854	95.4	3:6:9
No. 12204–9	Aug. 28, 1929	Sidewalk N	2002	3451	94.2	3:5:8
No. 12216–21	Aug. 26, 1929	Sidewalk S	892	1518	89.2	2½:6:7

The cubic foot blocks will be cut into 6 by 6 by 12-in. prisms for one- and two-year tests. This material was Cooksville Haydite. There was too much water and not enough cement. The mixing time was one minute, which is inadequate for this material.

Bridges 14 and 16.—The 28-day tests were 6 by 12-in. cylinders. The longer time test specimens were provided by sawing up the cubic foot blocks into prisms. They were of concrete made at the same time, but not from the same batch as the cylinders. Owing to the blocks being somewhat damaged while green, some of these specimens are not as reliable as they would have been had the compression tests been foreseen. A 3-minute mix was usual. This material was Kansas City Haydite. The test results up to the present time are as follows:

STRUCTURE	DATE	COMPRESSIVE STRENGTH, AVERAGE OF 5 SPECIMENS, LB. PER SQ. IN. 28 DAY	1 YEAR	2 YEARS	UNIT WEIGHT 24 HOURS, LB. PER CU. FT.
	BRIDGE 14. KANSAS CITY HAYDITE				
Floor	March 21, 1928	1831	3428	4061	105.5
Floor	March 22, 1928	2496	3739	4413	107.2
Sidewalk	April 2, 1928	2988	3755	4293	109.5
Sidewalk	April 4, 1928	2798	4349	4539	108.2
	BRIDGE 16. KANSAS CITY HAYDITE				
Floor	March 23, 1928	2570	3175	4060	107.7
Sidewalk	March 29, 1928	4000	4655	5359	111.3
	April 1, 1928	3343	4931	4858	113.4
	April 5, 1928	3598	5320	5210	108.9

Specimens remain to be tested at three, four, and five years. The mixes were approximately:

	FLOORS	SIDEWALKS
Haydite, ¾-in., damp loose	9	6
Haydite No. 6, damp loose	6	6
Cement, sacks	3¾	3½

STRUCTURE	DATE	UNIT WEIGHT LB. PER CU. FT.	COMPRESSIVE STRENGTH, 28 DAYS, LB. PER CU. FT.	APPROXIMATE FIELD MIX
	BRIDGE 11, COOKSVILLE HAYDITE			
Floor	March 1, 1930	93.4	1522	3¼:6:9
	March 1, 1930	94.5	1677	3¼:6:9
	March 6, 1930	96.3	2159	3½:6:9
	March 6, 1930	94.5	2007	3½:6:9
Averages		94.6	1841	
	BRIDGE 13, COOKSVILLE HAYDITE			
Floor	March 9, 1930	92.3	2508	3½:6:9
	March 9, 1930	92.6	2550	3½:6:9
	March 11, 1930	89.7	1857	3½:6:9
	March 11, 1930	92.3	2585	3½:6:9
Averages		91.7	2377	
	BRIDGE 18, COOKSVILLE HAYDITE			
Floor	February 22, 1930	91.5	2270	3½:6:9
	February 22, 1930	90.6	1649	3½:6:9
Averages		91.0	1959	

The wearing surface of the roadway is 1 in. of sheet asphalt. The Haydite is expected to give satisfactory surface on sidewalks without a wearing surface. The rough finish is considered an advantage. I am informed that it is proposed to resurface the deck of a heavily traveled bridge with Haydite concrete, omitting any special wearing surface. With proper precautions I believe it can be done.

It is our contention that the prospective user or contractor, in balancing the merits and demerits of the material, must add to the extra cost of the material the fact that workmanship and supervision must be better than good. Its low unit weight is indisputable, and there is no indication here that it will not stand the test of time.

MR. A. R. LORD[1] (*presented in written form*).—The user of Haydite has an impertinent question, in connection with Table X. All specimens reported were cured in the moist room for the full period until test. Job concrete is more likely to be cured (kept moist) for three to six days than for three to six months. It is observed, however, that Haydite concrete dries out very reluctantly even when exposed to the open air. Is there here indicated a curing value due to the moisture-retentive character of the Haydite? It would be of value to make a series of test up to ages of 6 months in which the cylinders were kept in the moist room for from one to seven days only and then stored in the open air until tested.

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[1] Lord & Holinger, Inc., Chicago, Ill.

The bulking of Haydite due to moisture is mentioned in the paper but no data given, such as would be useful on the job as a comparative guide. We would also like to know about the permeability and absorption of Haydite concrete. Volume changes have been mentioned earlier and should include "time yield" observations. Increased deflections were observed under the first loading of beams. Would this be further increased by continued loading to a greater or less degree than with ordinary concrete? How does Haydite concrete stand up under abrasion? How does Haydite affect the transmission and absorption of sound and of heat by concrete? The tests reported are exceedingly valuable and interesting but I hope that the investigation may continue until we have a satisfactorily complete knowledge of at least one of the hundreds of materials that call upon the busy engineer for recognition.

MR. A. W. MUNSELL.[1]—In connection with the investigation of light-weight aggregates for bridge deck slabs, we have conducted tests of beams which were made with Haydite aggregate with a trap rock wearing surface of the so-called sheet concrete type, that is, with a membrane between the courses. Three groups of specimens were made: first, with a burlap membrane with $\frac{3}{8}$-in. mesh; second, twisted cotton fabric of $\frac{1}{2}$-in. mesh; third, no membrane. The beams were 8 by 8 by 36 in. with a Haydite (fine and coarse) base course of $1:1\frac{1}{2}:3$ proportions 6 in. thick and 2 in. of $\frac{3}{8}$-in. trap rock and natural sand of the same proportions.

Samples sawed roughly into blocks of 8 by 8 by 6 in. of the three groups were subjected to freezing and thawing in a commercial refrigeration warehouse, where we were able to get temperatures of +4° F. Three series of tests were used in the freezing and thawing: namely, two samples of each group were thoroughly wet on all sides and immediately exposed in the refrigeration room; two samples of each group were submerged in water in a galvanized iron can and exposed in the refrigeration room. The third group, two from each group, were in a dry surface condition at all times.

The specimens were changed from freezing to thawing every 24 hours except Sundays and holidays. Altogether there were 122 cycles of freezing and thawing extending over a year when all of these tests were discontinued.

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[1] Engineer of Masonry Inspection, The Port of New York Authority, Jersey City, N. J.

The first and third series of tests showed no signs of failure after 122 cycles. On the second series, frozen solid at each alternation, after 25 cycles one of the specimens with the cotton fabric showed a complete separation between the courses at the membrane line, probably due to the cotton threads acting as channels for the water to penetrate between the courses. After 100 cycles all of the specimens in this series had failed, that is, the sawed ends of the specimens began to slough off and the Haydite could be brushed off which is due to the fact, as the authors have said, that the character of this aggregate is of a cellular structure with non-communicating cells and sawing has broken the cells and allowed water to enter and, with freezing, to disrupt the structure. It was noted that the sides against the form showed no sign of failure, showing that the mortar film on the specimen was a sufficient protection to keep the moisture from getting to the porous Haydite. I think the Haydite showed up very well under these conditions which were exceedingly severe and which would probably never occur in actual use.

MR. H. J. GILKEY[1] (*by letter*).—Mr. Lord[2] presents a picture of difficulties in placing Haydite concrete that could well intimidate the most venturesome of practical men. That such conditions have existed on some Haydite jobs is unquestioned. The fact that Richart and Jensen concluded that placing difficulties need not be excessive is most comforting and probably such a case as Mr. Lord mentions could be avoided by an improved but not a new technique in proportioning, mixing and handling.

The fact that Haydite concrete has about the same strength but a lower modulus of elasticity than concretes of usual aggregate suggests other very interesting possibilities for use in reinforced concrete, especially in columns and in beams reinforced for compression.

On the basis of the current design assumption that the modulus of elasticity of concrete is a direct function of its ultimate strength[3] it is only possible to stress compressive steel imbedded in concrete to 30,000 K in which $K = f_c/f'_c$, the reciprocal of the factor of safety for the concrete. For tied columns (Joint Code, Section 306) $K = 0.225$ and $f_s = 0.225 \times 30{,}000 = 6750$ lb. per sq. in., which is the maximum design compressive stress that can be used for the longitudinal steel in Joint Code tied column design, regardless of the quality of the concrete used. This conclusion is easily verified.[1]

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[1] Professor of Civil Engineering, University of Colorado, Boulder, Colo.

[2] A. R. Lord, *Journal*, Am. Concrete Inst., March, 1930, p. 23.

[3] Joint Code, Section 601.

On the other hand if the modulus of elasticity of the concrete is lowered without changing the ultimate strength (and therefore without changing the working stress) a corresponding increase follows in the load carried by the steel. If Haydite concrete of a given strength has a modulus of elasticity 25 per cent below that for stone concrete of equal strength, the mechanics of the problem call for a steel stress that is one third greater. A Joint Code column (if the code were altered in accordance with the mechanics involved) would then be designed for a 9000 lb. per sq. in steel stress and the same concrete stress as before. From the standpoint of design the economy is obvious. Similar reasoning applies to compressive reinforcement in beams and to spiralled columns.

The question now arises as to possible risk involved in thus increasing the stress in the column steel on account of the high steel stresses that result from shrinkage or flow of the concrete.[2]

Unfortunately test data on this phase of the problem are not yet available for Haydite concrete. In the absence of such data, there is a reasonable basis for concluding that no increased hazard would ensue. This tentative conclusion is based upon the following assumptions:

1. The amount of flow or shrinkage that the unreinforced Haydite concrete will undergo does not exceed that of ordinary concrete under similar circumstances.

2. The long-time (or flow) tensile modulus of elasticity of Haydite concrete does not exceed that for ordinary concrete.

Experiment may or may not show the first assumption to be true. If it is true, the total deformation that the steel might be called upon to take as a result of shrinkage would not exceed that for any other concrete and the resulting stress from this source would be no greater. The writer sees no reasonable basis for offering any guess as to the validity of this assumption. If the ultimate compressive deformations of the Haydite concrete were taken by Richart and Jensen, they might give an indication, although short-time test deformations and flow deformations are not necessarily comparable, especially when one set of deformations results largely from shrinkage and the other from stress of short duration.

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[1] *Engineering News-Record*, January 27, 1927, p. 166.

[2] W. A. Slater, *Journal*, Am. Concrete Inst., April 1930, p. 614, which refers in a general way to findings by F. R. McMillan and others.

It is evident that shrinkage stresses are an internal affair and that for those stresses not due to externally applied load, the compression in the steel creates an equal tension or reduced compression in the concrete. In general the short-time modulus for concrete in tension is closely equal to that in compression. If the tensile flow modulus for Haydite concrete is below that for ordinary concrete (which does not appear to be an unreasonable expectation) a greater shortening in the concrete could be prevented by a given induced compressive stress in the steel. This means that internal equilibrium would be established with relatively more of the deformation assumed by the concrete and less of it imposed on the steel. For a given tendency to shrink, the steel will be less severely stressed in compression. The fact that the concrete is called upon to assume greater tensile deformation is not likely to be objectionable in a compression member unless it is largely or entirely relieved of its normal compressive load, in which case high tensile stress might result in cracking.

The fact that the bond value is essentially the same as for other concretes removes questions regarding the normal transfer of load or interaction between concrete and steel.

Since lateral strains were evidently not measured, Poisson's ratio is an unknown quantity for the Haydite concrete, thus far. It is not possible therefore even to speculate regarding the Haydite spiralled column in comparison with one of ordinary concrete.

In dwelling thus at length on what is largely either elementary mechanics or supposition, the purpose has been to call attention to the fact that from the standpoint of design, as well as from the standpoint of weight, in Haydite concrete, or in other concretes that may be developed with similar properties, the engineer may have a more desirable material for columns and other compressive elements, than that which he is now using. At present a great deal of attention is being focused upon the reinforced-concrete column.[1] It would appear that reconnaissance tests on Haydite concrete, with a view to determining whether it may not have special adaptions in the field of compressive reinforced concrete members, might be very timely in the light of Richart's and Jensen's findings.

MR. F. N. MENEFEE[2] (*by letter*).—The writer offers the results of some tests made for the Lith-I-Bar Company in Kalamazoo not long ago on beams made of Haydite which may prove of interest by way of corroboration and supplementation. The tests were run to determine whether or not Haydite concrete poured and rolled into beams could be depended upon to follow the theory of reinforced concrete.

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[1] W. A. Slater, *Journal*, Am. Concrete Inst., April, 1930, p. 601.

[2] Professor of Engineering Mechanics, University of Michigan, Ann Arbor, Mich.

Along with the actual beam tests, studies of proportioning, resistance in compression and modulus of elasticity were made.

In the case at hand, one controlling feature of proportioning and water-cement ratio was the fact that the mixed matrix was dumped into a hopper, from where it fed onto a form traveling lengthwise of the beam, the bottom of which was shaped to form one side of the beam. This power-driven traveling form passed under rollers very similar to the way a hot billet passes under or between rollers in a steel mill. So while strength and all other desirable features were as much sought as in any concrete, the mixture had to be of such consistency as to come from under the high pressure rollers, well-shaped and uniform.

Tests for an ideal mixture were run, but the real control of mixture and water content was that condition of workability necessary to produce a material which would give great resistance to passing under the roller and yet form a reasonably smooth beam.

Two gradings of material were used, one ranging from very fine to 0.1 in. and the other from very fine to $\frac{3}{8}$ in. The theoretical ideal mixture proved to be 45 per cent of the coarse and 55 per cent of the fine. However, by trial at the plant it was found that the proportion which gave best results so far as manufacturing was concerned was 6 cu. ft. of fine, 4 cu. ft. of coarse and $1\frac{1}{2}$ cu. ft. of sand.

Direct Compression Tests:

Direct compression tests were made on standard 6-in. cylinders and on 1-ft. lengths of beams rolled without reinforcing. The results were as follows:

SPECIMEN	AGE	CURED	COMPRESSIVE STRENGTH LB. PER SQ. IN.
No. 1.—8-in. section	7 days	Air	1188
No. 2.—8-in. section	7 days	Air	843
No. 3.—8-in. section	7 days	Air	1520
		Average	1183
No. 4.—6-in. cylinder	21 days	Water	1685
No. 5.—6-in. cylinder	21 days	Water	1480
		Average	1582
No. 6.—8-in. section	27 days	Water	725
No. 7.—8-in. section	27 days	Water	1225
		Average	975

SPECIMEN	AGE	CURED	COMPRESSIVE STRENGTH LB. PER SQ. IN.
No. 8.—8-in. section	27 days	Air	1930
No. 9.—8-in. section	27 days	Air	1880
		Average	1905

It will be noted that specimens Nos. 1, 2 and 3 average 1183 lb. per sq. in. at 7 days, whereas the 28-day specimens, Nos. 8 and 9, average 1905 lb. per sq. in. These two groups were cured in moist air, and the ratio of increase in strength between 7 and 28 days is about the same as for gravel concrete.

Specimens Nos. 4 and 5 were cylinders cured in water; Nos. 6 and 7 were Lith-I-Bar sections cured in water. The test results indicate that excess water reduces the strength and the probable need for a slight change in the specifications governing curing of Haydite as compared with gravel concrete.

The maximum strength of 1900 lb. per sq. in., along with the appearance of the load deflection curves of the beams tested up to the load and deflection which produces a stress of 500 lbs. per sq. in., seems to justify the latter figure as a compressive working value for the concrete.

Tests for Modulus of Elasticity:

Tests for modulus of elasticity were run on short lengths cut from 8-in. beams rolled without reinforcement. In the use of such a specimen we included any effects which might arise from the rolling process. A 12-in. length of beam was cut and squared on the ends, then carefully set in plaster. Eight-inch Berry strain gages were placed on opposite sides (top and bottom when the beam is in natural position), the points being set in small brass lugs anchored in the concrete. The loads were applied in 1000-lb. increments corresponding to 625 lb. per sq. in. stress. Computing the modulus of elasticity for each increment of load gave values ranging from 3,250,000 lb. per sq. in. at the start to 1,670,000 lb. per sq. in. for a stress of 500 lb. per sq. in.

Tests on 8-in. Beams:

Two 1½-in. floor slabs of 13 ft. 1½ in. span resting on 8-in. Lith-I-Bar joists spaced 2 ft. apart with an overhang outside of each Lith-I-Bar of 1 ft. were tested for comparison. Two 8-in. beams without slab were tested on the same span. We thus had a floor slab 4 ft. wide in section resting on two 8-in. beams which in turn rested on regular concrete-block walls 13 ft. 1½ in. inside to inside. The beams were 32 and the slab 25 days old.

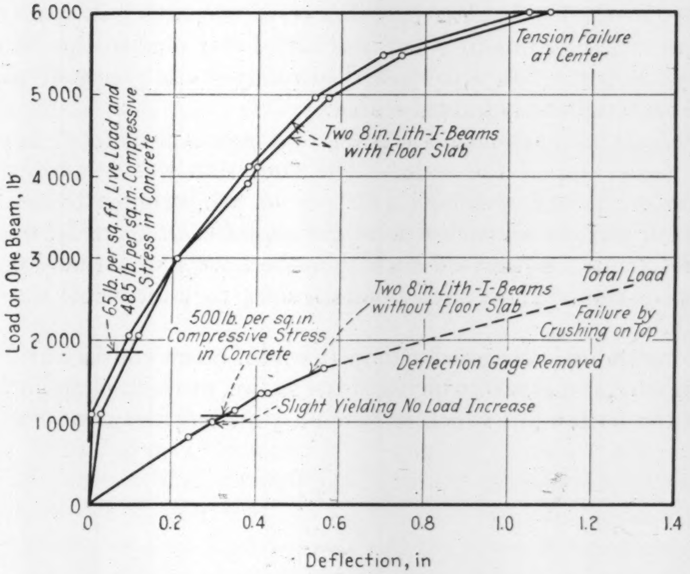

FIG. 1.—Load Deflection Diagram of 8-in. Beams With and Without Slab.

All data based on live loads.

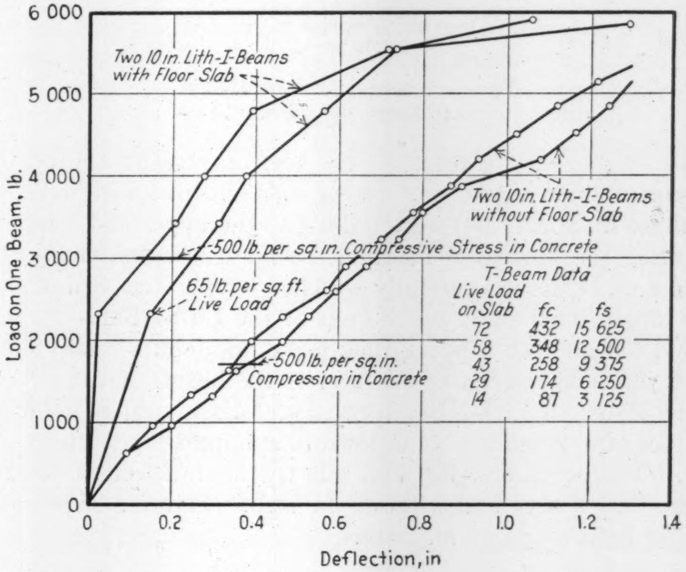

FIG. 2.—Load Deflection Diagram of 10-in. Beams With and Without Slab.

All data based on live loads.

The method of loading this slab structure, which in reality consisted of two T-beams in which the Lith-I-Bar formed the stem and the floor slab the flange, consisted of piling 80-lb. pieces of pig iron on the floor uniformly over the area.

Deflection of the beams was read by means of Ames dials placed under the center of the span. The floor slab was reinforced with $\frac{3}{8}$-in. rib metal lath, weighing 4 lb. per sq. yd., running transversely. The mesh was cut on each side of the top of each beam between the ribs and pressed downward such that the floor slab actually encased the top of the beam at such points from $\frac{3}{4}$ to 1 in. below the metal lath rib.

Longitudinal reinforcement in the 8-in. beam consists of a number 000 wire, the area of which is 0.104 sq. in., at the top, and a similar one at the bottom, to which is added a $\frac{1}{2}$-in. rod, the area of which is 0.196 sq. in., making a total area of tension steel in the bottom of the beam of about 0.3 sq. in. Shear rods of No. 3 wire were spaced vertically 6 in. apart, and were welded to the upper and lower rods.

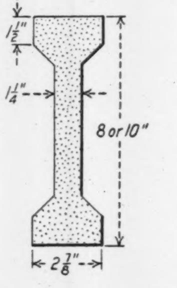

FIG. 3.—Showing Cross-Section of Both 8 and 10-in. Beams.

During the process of loading, the bond between the floor slab and the 8-in. beam was carefully watched for the first sign of slipping due to longitudinal shear on the top of the Lith-I-Bar. As near as we could tell no such slipping took place, for failure finally occurred through diagonal tension at one end of the beam, and it is believed that the slab and Lith-I-Bar formed a T-beam which followed the mechanics of a T-beam as laid down in standard texts, up to time of failure. The accompanying Fig. 1 is the load-deflection diagram of the 8-in. beams with and without the slab. Figure 3 shows a cross-section of both 8 and 10-in. beams.

Tests on 10-in. Beams:

The 10-in. beams were tested with and without slabs as in the case of the 8-in. beams. The slab was 2 in. thick reinforced with the same metal lath, cut between the ribs on either side of the top of the beam and pushed downward to assist in forming a bond between slab and beam. The beams were spaced 2 ft. center to center with a 1 ft. overhang, just as in the case of the 8-in. beam. The slab in this case was 2 in. thick and the span was 17 ft. 4 in. The beams were 33 days old and the slab slightly less.

Reinforcing consisted of an 000 wire top and bottom with an additional $\frac{5}{8}$-in. rod welded to the shear rod at the bottom just opposite the 000 wire. This gave an area of steel at the top of 0.103 sq. in. and at the bottom of 0.400 sq. in. The vertical rods were of No. 3 wire spaced 6 in. apart.

Figure 2 shows the load-deflection diagram of the 10-in. beam with and without slab with a table of stress in concrete and steel computed and placed on the diagram so that the load and stresses for any deflection up to that for 72 lb. per sq. ft. of slab may be read.

The weight of this concrete averaged 105 lb. per cubic foot.

MESSRS. F. E. RICHART[1] AND V. P. JENSEN[2] (*authors' closure by letter*).—Since the presentation of the paper, some changes have been made with regard to absorption allowances and the corresponding values of water-cement ratio. It was early recognized that absorption allowances were difficult to make since for a given time interval the absorptive capacity of Haydite depends upon whether it is initially dry or moist. Results of absorption tests on Haydite of various initial moisture conditions were reported recently by the authors.[3] Relations between strength and water-cement ratio are also presented, based on the data of Tables VI, VII, VIII and IX. Since the strength relations found are very nearly the same for all of the types of concrete noted, the absorption allowances as determined by tests of the aggregate are indirectly verified. This is in accord with Mr. Downie's suggestion that absorption allowances might be determined inferentially from strength data.

Mr. Downie's remarks are based on field experience and show the need of tempering laboratory data with the results of field practice. The authors appreciate that the Haydites used were not of ideal gradation and it is likely that much of the difficulty in their use is due to the large amount of very fine material. The small maximum size of the coarse material also necessitates a mix that with a larger coarse aggregate would be "oversanded." The 3-minute mix has been used in our laboratory tests for many years with all kinds of concrete. This is because of a relatively inefficient mixer and the desire to eliminate variability of mixing where it is not the quantity being studied. The determination of mixing water by "cut-and-try" methods is the usual one in the field. Greater refinements in determining the proper amount of mixing water are dependent upon more exact information on absorptive properties of aggregate than is generally available.

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[1] Research Associate Professor of Theoretical and Applied Mechanics, University of Illinois, Urbana, Ill.

[2] Special Research Assistant, Theoretical and Applied Mechanics, University of Illinois, Urbana, Ill.

[3] F. E. Richart and V. P. Jensen, "Construction and Design Features of Haydite Concrete," *Journal*, Am. Concrete Inst., October, 1930, p. 151.

Mr. Lord points out a possible curing effect due to the moisture-retentive character of Haydite concrete. A small series of tests made on cylinders moist cured for 7 days then stored in air for periods up to 6 months showed some increase in strength of Haydite concrete with age, but also, contrary to expectation, showed a similar increase in strength of gravel concrete. It is planned to make a further, more comprehensive set of tests on this subject. Other questions raised by Mr. Lord point to the need of further important investigation; so far as is known there is no answer to them at present.

The freezing-and-thawing tests by Mr. Munsell provide interesting and valuable data regarding durability of the material.

In answer to Mr. Gilkey's suggestions on the design of Haydite compression members, reference is again made to the article by the authors that has just been published,[1] where reference is made to the short-time plastic deformation of gravel and Haydite concrete under compressive stress. Tests of reinforced concrete columns have indicated no advantage for Haydite concrete over gravel concrete due to the difference in moduli of elasticity.

The tests of Haydite beams cited by Mr. Menefee are instructive. The high value of the initial modulus of elasticity of 3,250,000 lb. per sq. in. found for Haydite concrete of a strength below 2000 lb. per sq. in. is noteworthy. From the fact that the modulus of elasticity decreased to 1,670,000 lb. per sq. in. at a stress of 500 lb. per sq. in., it appears that there was considerable initial curvature in the stress-strain curves, a phenomenon not generally observed in the tests made by the authors.

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[1] *Loc. cit.*

FLOW OF CONCRETE UNDER SUSTAINED COMPRESSIVE STRESS

BY R. E. DAVIS[1] AND H. E. DAVIS[2]

SYNOPSIS

This paper describes laboratory tests on concrete cylinders to determine the effect of compressive stress sustained over a considerable period of time. The deformation due to stress which takes place subsequent to the application of load and which increases with time is here designated as "flow," a quantity separate from changes in dimension due to causes other than stress, such as variations in temperature and moisture conditions.

The tests were made to determine the manner in which flow is influenced by (1) time, (2) richness of mix, (3) gradation of aggregate, (4) kind of aggregate (5) water-cement ratio, (6) magnitude of stress, (7) age, (8) moisture conditions, (9) reinforcement, and (10) stress alternations.

Among other things it has been found that flow (1) continues to increase for a long period of time, (2) is greater for a concrete when dry than for the same concrete when wet, (3) is materially affected by the kind of aggregate, (4) is less for rich mixes than for lean ones, (5) is greater for a high water-cement ratio than for a low one, and (6) increases rapidly with the magnitude of sustained stress. Longitudinal reinforcement appreciably reduces both flow and shrinkage, but in time the stress in the steel may become several times greater than that existing immediately upon application of the load. The effect of flow is to increase the instantaneous modulus of elasticity, but it does not influence the compressive strength.

INTRODUCTION

It has long been recognized that concrete is not a perfectly elastic material, but is a material which, when subjected to stress, continues to yield or deform over a long period of time. That is, not only does the stress-strain relation of a given concrete vary with the intensity of the stress but also with the length of the period over which the stress is applied. This property of yielding with the passage of time has been variously designated "time yield," "time deformation," "plastic deformation" and "plastic flow." In this report the term "flow" will be employed, as being short and meaningful—though it seems questionable whether there actually occurs in concrete a movement of the particles over one another after the manner we commonly associate with the "flow" of any material.

In this paper the term "flow" will be taken to mean that deformation which takes place subsequent to the application of load; that is, the flow at the end of any interval of time is the deformation due to the sustained load and not due to the instantaneous application of the load. It is the total deformation due to stress minus the deformation observed immediately upon application of the load. It does not include changes in length due to causes other than stress, such as variations in temperature and variations in moisture conditions surrounding the specimens.

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[1] Professor of Civil Engineering, University of California, Berkeley, Calif.

[2] Instructor in Civil Engineering, University of California, Berkeley, Calif.

Since concrete under the action of sustained stress is imperfectly elastic, it seems improper to use the term "modulus of elasticity" as being the ratio of unit stress to unit deformation when plastic deformations occurring with the passage of time are included; consequently, in this report the term "modulus of elasticity" will merely refer to the ratio of unit stress to unit deformation occurring immediately upon the application of load, and the term "modulus of resistance" will be used to designate the ratio of unit stress to total unit deformation after any interval of time, this total including the deformation occurring immediately upon application of the load plus the deformation, due to stress, occurring subsequent to the application of load.

The experimental work reported herein has been in progress since the summer of 1925, when a series of tests was started on plain concrete cylinders held in compression. The tests have from time to time been extended until at present 215 specimens are, or have been, under observation. The tests have been designed to show the effect upon the time-flow relation of the following:

1. Richness of mix,
2. Water-cement ratio,
3. Character and gradation of aggregate,
4. Age at time of loading,
5. Magnitude of stress,
6. Variations in moisture conditions,
7. Length of period of sustained stress,
8. Reinforcement, and
9. Alternately applying and releasing load.

In addition, tests have been made to determine the effect of flow upon strength and modulus of elasticity.

SCOPE OF TESTS

The tests may be divided into seven series, as follows:

Series I.—Inaugurated in 1925 to determine the effect of richness of mix, water-cement ratio and gradation of aggregate upon the flow.

Series II.—Inaugurated in 1926 to determine the effect of magnitude of unit stress, age at time of loading and moisture conditions of storage upon flow.

Series III.—Inaugurated in 1928, further to determine the effect of humidity of the atmosphere upon flow.

Series IV.—Inaugurated in 1928 to determine the effect of character of the mineral aggregate upon flow.

Series V.—Inaugurated in 1929 to determine the effect of alternations of sustained load upon flow.

Series VI.—Inaugurated in 1929 to determine the effect of reinforcement upon flow.

Series VII.—Inaugurated in 1929 to determine the effect of flow upon modulus of elasticity and compressive strength.

The specimens have been in the form of cylinders varying from 4 to 10 in. in diameter and from 12 to 24 in. in length.

The principal specimens have been subjected to sustained compressive stress for each series. Auxiliary or control specimens subjected to the same conditions as regards curing and storage as the principal specimens, but under no stress, have been under observation in order to determine the changes in dimensions due to causes other than stress.

Further details regarding the specimens of the several series and the conditions surrounding the tests are given later in the articles describing the individual series.

TESTING APPARATUS AND TESTING METHODS

Observations of changes in length of the specimens have been determined for the most part by the use of a fulcrum-plate strain gage, the strain gage points being of stainless steel screwed into brass plugs cast in the specimens. On each cylinder are 3 longitudinal gage lines at the third points of the circumference. The gage length employed in Series I was 20 in.; for all other series the gage length has been 10 in.

In each loaded specimen the load has been maintained constant by means of one or more car springs held in compression by a system of rods and plates between which the specimen is clamped. The desired load is applied by mounting this apparatus in a testing machine with a cylinder in position, the load being indicated by the machine. In order to eliminate the disturbing influence of variable temperature, a small portable machine has been built specially for applying loads to these specimens, and this machine is placed in one of the constant temperature rooms where the specimens are stored. When a specimen is loaded, the nuts on the rods of the load-sustaining apparatus are brought to a bearing against the end plates. The load on the testing machine is then released and the compression in the car spring and in the specimen is maintained by tension in the rods. This method of maintaining stress has proved very satisfactory, since the specimens may be moved about and placed in any position after the load has once been applied, without disturbing stress conditions.

For each group of loaded specimens there is a corresponding group of unstressed or control specimens which is stored in the same conditions as the loaded specimens. Observations made upon these control specimens (made simultaneously with observations on loaded specimens) give changes in length due to causes other than stress, and this makes it possible to determine the flow which has occurred in the loaded specimens as a quantity separate from volume changes due to variations in moisture or temperature.

All specimens have been stored continuously at 70° F. in specially insulated rooms heated by electricity and equipped with sensitive thermostats. Furthermore those stored in air have been placed in rooms where the humidity is controlled as well. Under normal conditions variations from the established standard do not exceed 1° F. in temperature and 1 per cent in relative humidity.

TEST OF SERIES I

Conditions:

The purpose of these tests was to determine the effect upon flow of (1) richness of mix, (2) gradation of aggregate, and (3) water-cement ratio. The tests were begun in May, 1926.

The specimens were 6 by 24-in. cylinders, 16 in number, 12 of which were subjected to a continuous compressive stress of 640 lb. per sq. in. and 4 of which were maintained in an unstressed condition. All specimens were cured for 2 months in water and 5 months in air prior to the application of load. After the beginning of the loading tests, all specimens, including those of the unstressed group, were stored in an atmosphere of 70° F. and 78 per cent relative humidity.

Four concrete mixes were investigated, differing from one another either in regard to richess or to gradation of aggregate, all as indicated in the following table:

	CEMENT-AGGREGATE RATIO		FINENESS MODULUS	WATER-CEMENT
MIX	BY VOLUME	BY WEIGHT	OF AGGREGATE	RATIO BY VOLUME
No. 1..........	1:3.4	1:4	6.43	0.81
No. 2..........	1:3.4	1:4	3.52	1.06
No. 3..........	1:5.9	1:7	6.43	1.01
No. 4..........	1:5.9	1:7	3.52	1.42

The concrete was designed to have a relative consistency of 1.25. For mixes of low fineness modulus (mixes 2 and 4) the aggregate was composed of Niles top gravel, a Coast Range sand all of which passed a No. 4 sieve. For the mixes of high fineness modulus the fine aggregate was Niles top gravel and the coarse aggregate was a crushed metamorphic sandstone between the sizes ½ and 1½ in. from the local quarries of the Oakland Paving Co. From each mix there were manufactured four specimens, three of which were loaded and one of which maintained without stress.

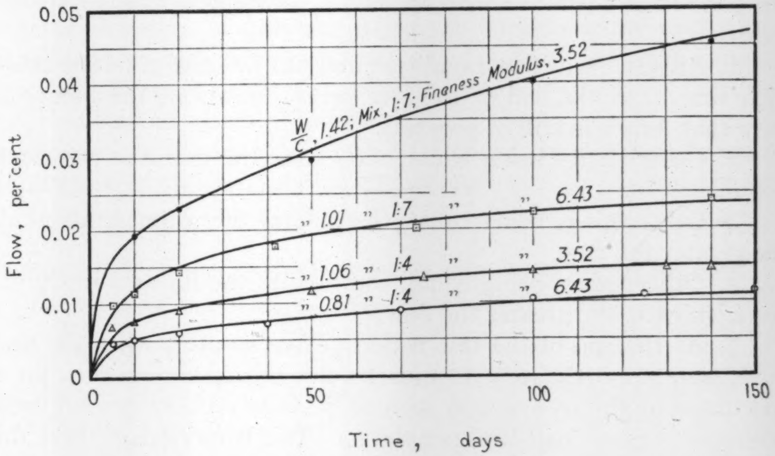

FIG. 1.—Effect of Richness of Mix and Gradation of Aggregate Upon Flow.

Age at time of loading, 7 months.
Stress, 640 lb. per sq. in.
78 per cent relative humidity.

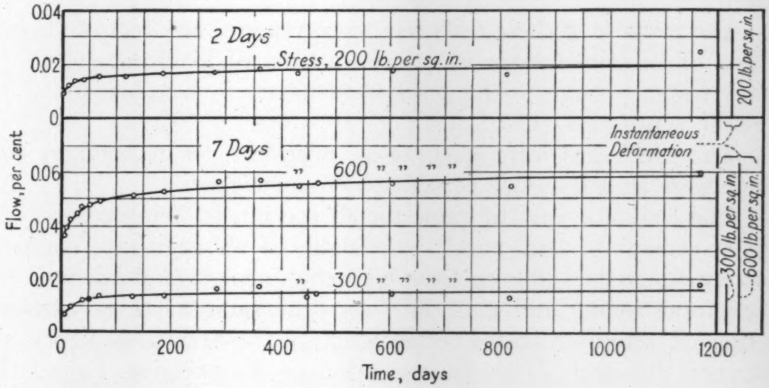

FIG. 2.—Effect of Age at Loading and Stress Upon Flow, Series II. Ages 2 and 7 days, Water Storage.

Results:

The results are shown graphically in Fig. 1, for which the ordinates are flows in terms of percentage of length and the abscissas are periods of sustained load in days. Consulting the curves it is seen that:

1. All specimens flow rapidly at first but the rate of flow decreases with time. At the end of the test period, however, the indications were that flow was still in progress.

2. Other things being equal, the leaner the mix, the greater the flow.

3. Other things being equal, the greater the water-cement ratio, the greater the flow.

4. Other things being equal, the smaller the fineness modulus of the aggregate, the greater the flow.

5. At the end of the test period of five months, when the specimens were approximately 12 months old, the maximum flow for the specimens of the lean mix is seen to be nearly 0.05 per cent, which amounts to more than $\frac{1}{2}$ in. per 100 ft. This is more than three times the flow of the corresponding concrete of the rich mix.

TESTS OF SERIES II

Conditions:

The purpose of these tests was to determine the effect of (1) magnitude of sustained stress, (2) age at time of loading, and (3) air *versus* water storage. The tests were begun in October, 1926, and are still in progress.

The specimens were 4 by 14-in. cylinders, 58 in number, 40 of which were loaded and 18 of which were unstressed.

The concrete was the same for all specimens, being composed of 1 part cement to 5.05 parts, by weight, of an aggregate composed entirely of crushed granite for which the fineness modulus was 5.03. The proportioning and materials were the same as those employed in the concrete used in the construction of the Stevenson Creek Test Dam of the Arch Dam Investigation of Engineering Foundation. The water-cement ratio was 1.03 by volume and the average slump was 3.2 in. The mix data are given in the following table:

	CEMENT	FINE AGGREGATE	MEDIUM AGGREGATE	COARSE AGGREGATE
Proportions by Weight........	1	3.01	1.15	0.89
Sieve sizes..................	..	Below $\frac{3}{8}$ in.	$\frac{3}{8}$ to $\frac{3}{4}$ in.	$\frac{3}{4}$ to $1\frac{1}{2}$ in.
Fineness Modulus............	..	3.27	6.72	8.78

In Table I are given the storage and stress conditions investigated. Examining the table it will be found that the age at time of loading varied from 2 days to 3 months and that the intensity of sustained stress varied from 200 to 1200 lb. per sq. in. In general, observations were made upon 3 control specimens for each age of loading and storage condition, and observations were made upon 3 loaded specimens for each age of loading, storage condition and intensity of sustained stress. For those specimens stored in water, the temperature of the bath was 70° F., and for those stored in air the temperature of the surrounding atmosphere was 70° F. and the relative humidity was 70 per cent.

TABLE I.—STORAGE AND STRESS CONDITIONS OF SPECIMENS IN SERIES II.

CURING	STORAGE AFTER LOADING	AGE AT LOADING	STRESS, LB. PER SQ. IN.
Water...............	Water.................	2 days	200
Water...............	Water.................	7 days	300 600
Damp Sand..........	Water.................	28 days	300 600 900
Damp Sand..........	Water.................	3 months	600 900 1200
Damp Sand..........	Air at 70 per cent relative humidity.............	28 days	300 600 900
Damp Sand..........	Air at 70 per cent relative humidity.............	3 months	600 900 1200

Results:

The results of the tests are shown graphically in Figs. 2 to 5, inclusive, where for each age and condition of storage the relation between flow and time is shown for the various stress intensities. At the extreme right of each of these figures there are indicated by vertical lines the magnitudes of the instantaneous deformations, or those taking place immediately upon application of the load.

Consulting the figures, it is seen that under none of the conditions is there evidence that flow has actually ceased, even though the specimens have been under load for 1200 days. Further it will be noted that, while under conditions of water storage the rate of increase of flow at the later ages was small; under conditions of air storage, flow was increasing at a substantial rate. From these data it may be concluded that:

1. Flow under constant load continues to increase for a long period of time.

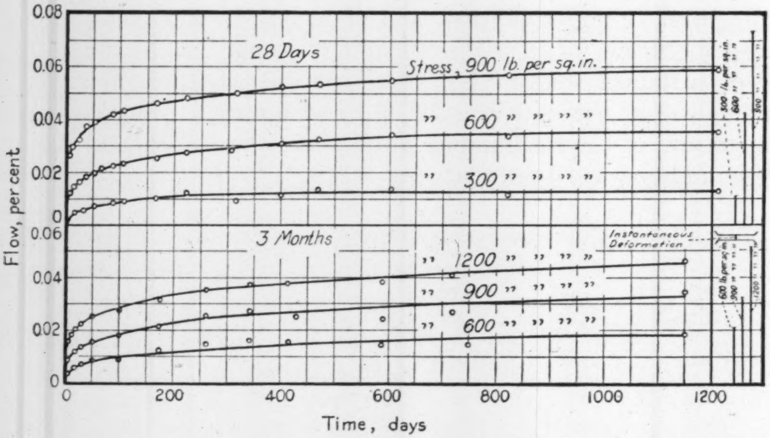

FIG. 3.—Effect of Age at Loading and Stress Upon Flow, Series II. Ages 28 Days; 3 Months, Water Storage.

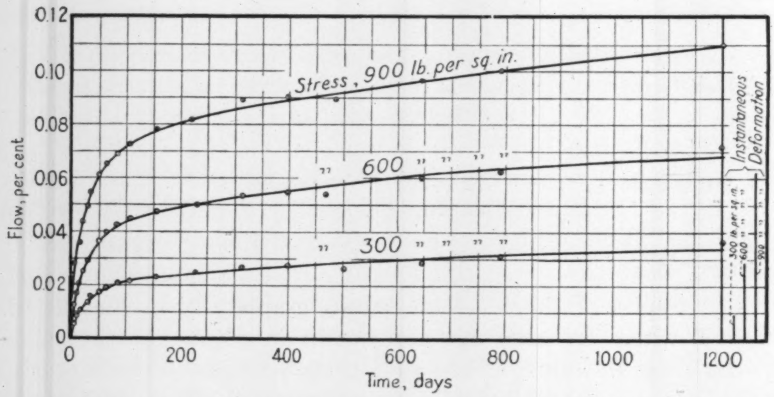

FIG. 4.—Effect of Age at Loading and Stress Upon Flow, Series II. Age at Loading 28 Days, Air Storage.

2. Other things being equal, the higher the sustained stress, the greater the flow.

3. Under conditions of air storage, the long-time flow becomes several times greater than the instantaneous deformation or that which takes place as the load is first applied.

4. Other things being equal, the flow of concrete stored under water is considerably less than that of concrete stored in air. Compare Fig. 3 with Figs. 4 and 5. A few values for a period of 1000 days of sustained load taken from the figures are tabulated:

Flow, per cent	Flow in per cent after 1000 Days of Sustained Load, Series II					
	Age at Loading, 28 days			Age at Loading, 3 months		
	Stress, 300 lb. per sq. in.	Stress, 600 lb. per sq. in.	Stress, 900 lb. per sq. in.	Stress, 600 lb. per sq. in.	Stress, 900 lb. per sq. in.	Stress, 1200 lb. per sq. in.
Water Storage	0.012	0.035	0.058	0.018	0.032	0.045
Air Storage	0.033	0.067	0.105	0.058	0.086	0.131

For the conditions illustrated, the dry concrete deformed two to three times as much as the wet.

5. Other things being equal, the greater the age of concrete at time of loading, the less the flow after a given period of sustained load. From Figs. 2, 3, 4 and 5, the following values are taken. The period of sustained stress is 1000 days:

Age at Loading	Flow in per cent after 1000 Days of Sustained Load, Series II				
	Water Storage			Air Storage	
	Stress, 300 lb. per sq. in.	Stress, 600 lb. per sq. in.	Stress, 900 lb. per sq. in.	Stress, 600 lb. per sq. in.	Stress, 900 lb. per sq. in.
7 days	0.016	0.057	.....	.....	.....
28 days	0.012	0.035	0.058	0.067	0.105
3 months	.....	0.018	0.032	0.058	0.086

6. As defined previously, the modulus of resistance is the ratio of unit stress to total unit deformation after a given period of time. The values in the following table have been taken from stress-strain curves plotted for the indicated periods of sustained stress:

Period of Sustained Stress	Modulus of Resistance, lb. per sq. in., at a Stress of 800 lb. per sq. in.			
	Air Storage		Water Storage	
	Age at Loading, 28 days	Age at Loading, 3 months	Age at Loading, 28 days	Age at Loading, 3 months
Instantaneous	1 630 000	2 720 000	1 260 000	2 760 000
7 days	1 090 000	1 640 000	930 000	2 200 000
30 days	870 000	1 370 000	860 000	1 950 000
3 months	730 000	1 170 000	810 000	1 810 000
6 months	680 000	1 010 000	....	....
1 year	640 000	740 000	740 000	1 530 000
2 years	590 000	670 000	710 000	1 480 000
3 years	560 000	620 000	700 000	1 420 000

These values show that the modulus of resistance decreases with the length of time after load is applied, at first rapidly, then more slowly, until after a considerable period it is but a fraction of the instantaneous modulus of elasticity exhibited immediately upon application of the load. It is also seen that the modulus of resistance decrease less rapidly for wet concrete than for dry concrete.

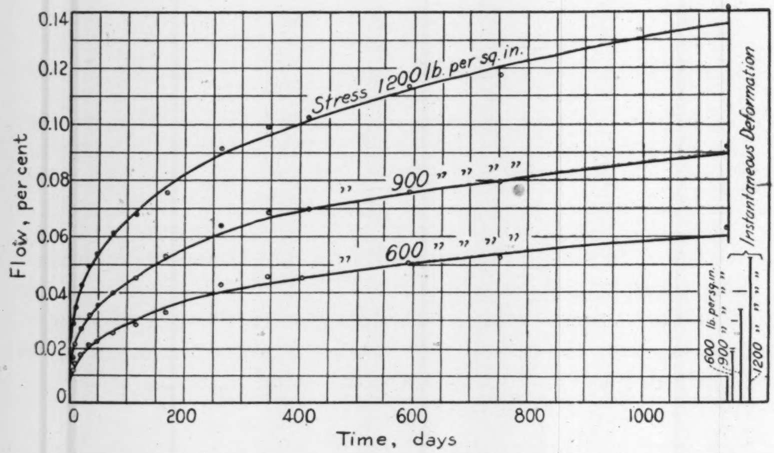

FIG. 5.—Effect of Age at Loading and Stress Upon Flow, Series II. Age at Loading 3 Months, Air Storage.

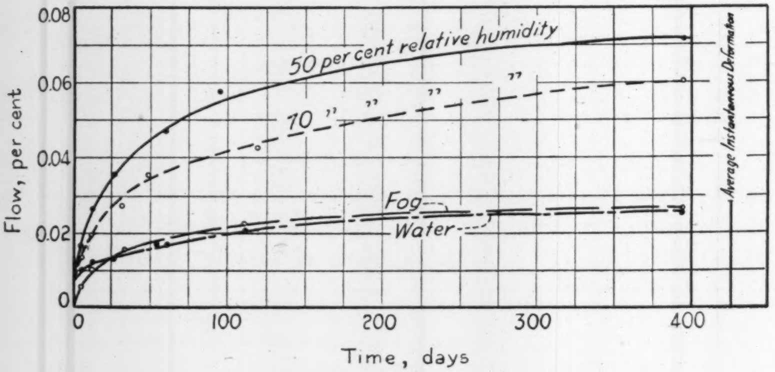

FIG. 6.—Effect of Moisture Conditions Upon Flow.

Since the modulus of resistance is but the reciprocal of the total unit deformation multiplied by the sustained unit stress, the conditions which affect flow likewise affect the modulus.

TESTS OF SERIES III

Conditions:

The purpose of these tests was to determine the effect upon flow of variations in the conditions of storage with regard to moisture. The conditions of storage which were included in the investigation were (1) air at 50 per cent relative humidity, (2) air at 70 per cent relative humidity, (3) fog, and (4) under water. The tests were begun in October, 1928, and are still in progress.

The specimens were 4 by 14-in. cylinders, 20 in number, 12 of which were loaded and 8 of which were used as unloaded controls.

The concrete was the same for all specimens, being composed of 1 part of cement to 5.67 parts by weight of Niles gravel. The mix data are given in the following table. The fineness modulus of the mixed aggregate was 5.61 and the water-cement ratio was 0.89:

	CEMENT	FINE AGGREGATE	MEDIUM AGGREGATE	COARSE AGGREGATE
Proportions by Weight......	1.00	2.00	1.67	2.00
Fineness Modulus...........	....	3.48	5.99	7.40

The specimens were fog-cured for 28 days when those carrying a sustained stress were all loaded to 800 lb. per sq. in. For each of the four conditions of storage there were three loaded and two control specimens.

Results:

The results of the tests are illustrated by Fig. 6 in which there is shown a time-flow curve for each of the several moisture conditions. At the extreme right of the figure, magnitude of the instantaneous deformation is given by the vertical line. From a study of the figure it will be observed that:

1. The drier the conditions of storage during the period of sustained stress, the greater the flow of a given concrete.
2. Concrete stored under water flows substantially the same as that stored in fog.
3. The flow after a year of sustained stress was as follows:

	FLOW
Storage in air at 50 per cent relative humidity.......	0.075 per cent
Storage in air at 70 per cent relative humidity.......	0.060 per cent
Storage in fog....................................	0.027 per cent
Storage in water..................................	0.026 per cent

4. The flow under conditions of air storage (50 and 70 per cent relative humidity) at the end of a year is very much greater than the instantaneous deformation at the time of loading.

TEST OF SERIES IV

Conditions:

The purpose of these tests was to determine the effect of the character of mineral aggregate upon flow. The aggregates which were included in the investigations included (1) Niles gravel, containing quartz, sandstones, granites, etc., (2) metamorphic sandstone from Oakland, Calif., (3) quartz, (4) basalt from Napa, Calif., (5) limestone from Santa Cruz, Calif., and (6) granite. The tests were begun in October, 1928, and are still in progress.

The specimens were 4 by 14-in. cylinders, 30 in number, of which 18 were loaded and 12 were used as controls.

The concrete was of the same richness of mix for all specimens, namely, 1 part of cement to 5.67 parts by weight of mixed aggregate. The water-cement ratio was uniformly 0.89 by volume.

For the gravel concrete, the mix and gradation were as indicated under Series III. Other aggregates were crushed, screened in a variety of sizes, and then these sizes recombined to give a sieve analysis curve practically the same as that of the gravel. That is, the gradation of one mixed aggregate was the same as for all others. The fineness modulus of each mixed crushed aggregate was 5.75.

The consistency of the fresh concrete for the several aggregates, as determined by slump and flow tests was a follows:

AGGREGATE	SLUMP, IN.	FLOW
Gravel	4	141
Sandstone	2¼	138
Quartz	4¼	156
Basalt	3	137
Limestone	2	137
Granite	3½	142

The specimens were fog-cured until loaded at the age of 28 days and were thereafter stored in air at 50 per cent relative humidity. For each aggregate, three specimens were loaded to a stress of 800 lb. per sq. in. and two specimens were employed as unstressed controls.

Results:

The results are shown graphically in Fig. 7, where for each aggregate there is a curve showing the relation between flow and time. Also at the extreme right of the figure are given for each aggregate the instantaneous deformations accompanying the application of load. From the figure it appears that:

1. The character of the mineral aggregate has a marked effect upon flow. The sandstone and basalt concretes exhibit greatest flow

and limestone concrete the least. After a year of sustained load, quartz, granite and gravel concretes all exhibit intermediate values.

2. For the first few days, the gravel concrete deformed at about the same rate as the sandstone concrete, but the rate of flow rapidly decreased thereafter so that at the end of a year it had deformed no more than the specimens of quartz and granite.

3. The approximate values of the flow at the end of a year are:

	FLOW
Sandstone and Basalt Concrete	0.10 per cent
Gravel, Granite and Quartz Concrete	0.07 per cent
Limestone Concrete	0.05 per cent

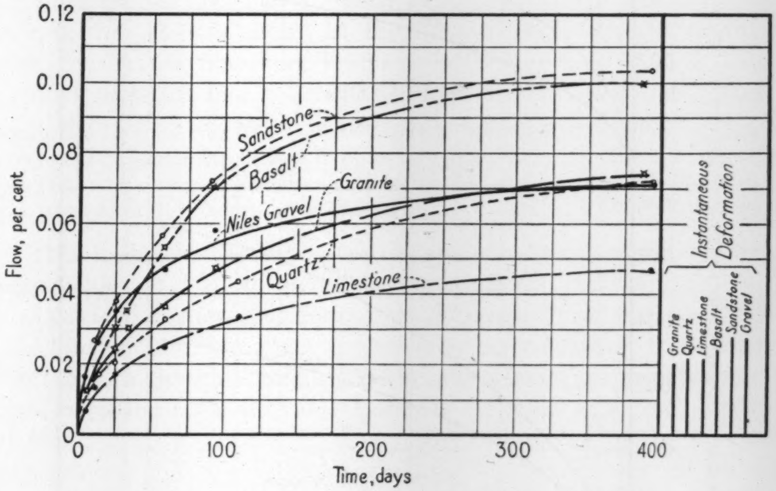

FIG. 7.—Effect of Kind of Aggregate Upon Flow.

TESTS OF SERIES V

Conditions:

The purpose of these tests was to determine the effect of steel reinforcement upon flow, and also to learn if axial flow produced by compressive stress is accompanied by a lateral or transverse flow. It was felt not improbable that there might be a lateral flow at right angles to the direction of stress just as there is an instantaneous lateral deformation which is produced as the load is applied. The tests were begun in March, 1929, and are still in progress.

The specimens are 10 by 20-in. cylinders, 4 in number, 2 of which are plain and 2 of which are reinforced with longitudinal bars and spiral hooping. The reinforcement consists of six $\frac{1}{2}$-in. square deformed bars, and an 8-in. diameter spiral of No. 6 A.S.W.G. of $1\frac{1}{4}$-in. pitch. The steel is of structural grade and the ends of the longitudinal bars are ground flush with the ends of the cylinders. Considering the core area, the steel ratio for longitudinal bars is 0.0298 and for spiral is 0.0133. Considering the entire cross-section of the cylinder, the steel ratio for the longitudinal bars is 0.0190.

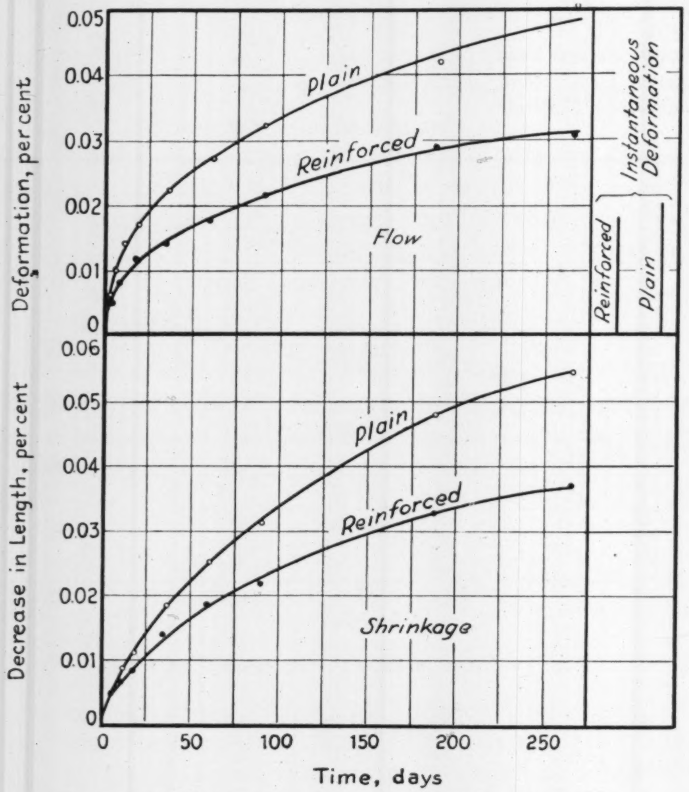

FIG. 8.—Effect of Reinforcement Upon Shrinkage and Flow.

The concrete is composed of 1 part of cement, to 2.64 parts of Niles sand to 2.32 parts crushed sandstone, all by volume. The fineness modulus of the combined aggregate was 5.22 and the water-cement ratio was 0.86. The slump was 2 in.

The specimens were cured in fog for 50 days and thereafter were stored in air at 50 per cent relative humidity. At the age of 60 days, one plain and one reinforced specimen were loaded. The stress in the plain concrete was 800 lb. per sq. in. and the stress in the reinforced concrete at the time of loading was calculated to have been 775 lb. per sq. in. on the full concrete area.

Results:

Figure 8 shows the effect of steel reinforcing on three types of deformation: instantaneous, flow, and shrinkage due to drying. The instantaneous deformations are almost the same for both the plain and reinforced specimens and would have been more nearly equal had the stress in the concrete been the same for each type of specimen. The flow, after any period of time, is naturally less for the reinforced than for the plain concrete, since as deformation takes place, more and more load is taken by the steel, and the stress in the concrete is diminished. As was shown in the tests of series II, the lower the stress, the less the flow.

An interesting fact is brought to light by the following figures:

Stress in Steel Reinforcing Due to Instantaneous Deformation.	5 600 lb. per sq. in.
Stress in Steel Reinforcing Due to Flow for 250 days........	9 400 lb. per sq. in.
Stress in Steel Reinforcing Due to Shrinkage for 250 days....	10 800 lb. per sq. in.
Total Stress in Steel 250 days After Loading................	25 800 lb. per sq. in.

This indicates that the steel is already over-stressed as far as design values go. It will perhaps soon reach the yield point.

As stated earlier, this series was designed to determine whether or not longitudinal flow is accompanied by lateral flow. To determine lateral flow, a device consisting essentially of two micrometer microscopes mounted on a horizontal axis is clamped in a fixed position and the lateral movement of silver targets inserted in the specimen are measured. While lateral shrinkage has been observed to take place, within the precision of observation no lateral flow has been detected.

TESTS OF SERIES VI

Conditions:

The purpose of these tests was to determine the behavior of concrete under alternations of a maximum and a minimum sustained stress. Observations were made to determine the instantaneous and time yields each time the load was increased from minimum to maximum and the instantaneous and time recoveries each time the load was decreased from the maximum to the minimum. The tests were begun in January, 1930, and are still in progress.

The specimens are 4 by 14-in. cylinders, 30 in number, 18 of which are subjected to load alternations and 12 of which are unstressed control specimens.

The concrete was the same for all specimens. The mix by weight was composed of 1 part of cement to 5.68 parts of mixed aggregate. The mix data are given below. The fineness modulus of the combined aggregate was 4.86 and the water-cement ratio was 0.85. The slump was 4 in.:

	CEMENT	MONTEREY SAND	NILES SAND	NILES GRAVEL
Proportions by Weight............	1	1.14	1.14	3.40
Fineness Modulus................	..	1.74	2.90	6.72

The specimens were fog-cured for 28 days, when load alternations were begun. Thereafter half the specimens were stored in air at 50 per cent relative humidity and the remainder were stored under water.

For all specimens the maximum sustained stress was 800 lb. per sq. in. and the minimum sustained stress was 40 lb. per sq. in. A stress alternation consisted of a given period at the maximum stress followed by a like period at the minimum stress. For one-third of the stressed specimens in both air and water, the period of alternation, or stress cycle, was two days; for a second group of equal number the period was 10 days; and for a third group of equal number the period was 60 days.

Results:

The measured deformations for each of the three groups have been plotted against time as shown in Figs. 9, 10 and 11. For Figs. 9 and 10, the upper diagram gives the results for specimens stored in water and the lower diagram gives the results for specimens in air. The full lines of the diagrams are vertical and represent the instantaneous yield or recovery; the dash sloping or curved lines represent the time flow or recovery. Figure 9 gives the results of fifteen 2-day alternations, Fig. 10 shows six 10-day alternations, and Fig. 11 presents the graphs for a single 60-day alternation.

A study of these figures makes it appear that:

1. The instantaneous deformation which took place at the time of first applying the load was greater, in every group, than any succeeding value of the deformation or recovery, showing that a permanent set takes place.
2. The instantaneous deformation and instantaneous recovery tend to become less with age, except in the case of the dry storage, 2-day period group.
3. The rate of the time flow and time recovery tends to become less with age.
4. The residual deformation in the concrete increases as the number of stress cycles is increased.

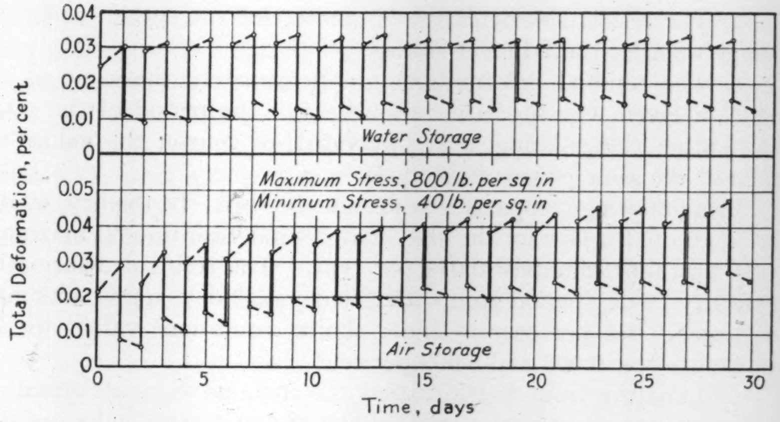

FIG. 9.—Effect of Stress Alternations, 2-Day Cycles.

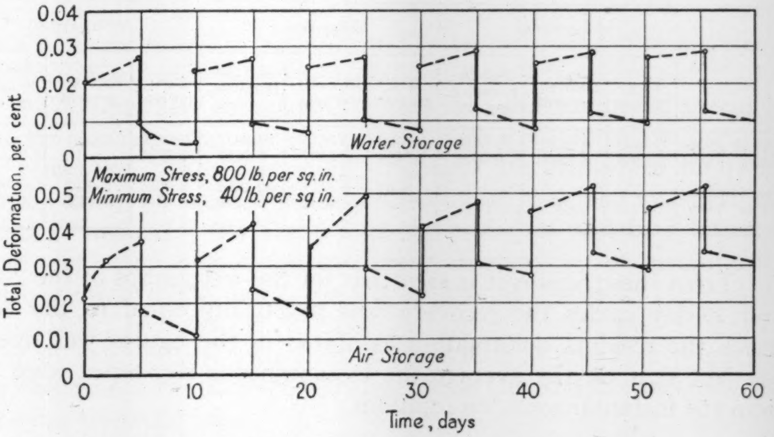

FIG. 10.—Effect of Stress Alternations, 10-Day Cycles.

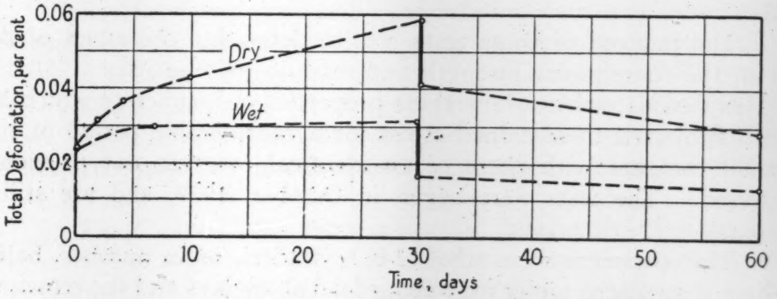

FIG. 11.—Effect of Stress Alternations, 60-Day Cycles.

5. The residual deformation is greater for the specimens in dry storage than for those in wet storage.

6. The residual deformation is approximately the same at the end of a given length of time regardless of the period of the stress cycle, other things being equal, provided, of course, the values are taken at the same phase of the cycle.

The following comparison is of some interest: In the dry, 60-day period group, the flow for the first 30 days (under continuous maximum load) was approximately 0.034 per cent. The residual deformation in the dry 10-day period group after 60 days (30 days under maximum load) was 0.031 per cent. Under similar conditions values for the wet group were 0.008 and 0.009 per cent.

Eliminating from consideration the instantaneous deformations or instantaneous recoveries, and adding the successive values of flow and recovery, the deformations given below are determined:

		2-day Period			10-day Period			60-day Period		
		Flow, per cent	Recovery, per cent	Net Deformation, per cent	Flow, per cent	Recovery, per cent	Net Deformation, per cent	Flow, per cent	Recovery, per cent	Net Deformation, per cent
After 30 Days	Wet	0.0323	0.0337	—0.0014	0.0132	0.0115	0.0017	0.0086	......	......
	Dry	0.0685	0.0381	0.0304	0.0389	0.0207	0.0182	0.0365	......	......
After 60 Days	Wet	......	......	......	0.0207	0.0213	—0.0006	0.0086	0.0035	0.0051
	Dry	......	......	......	0.0597	0.0317	0.0280	0.0365	0.0130	0.0235

From these figures it is seen that for the wet groups of the 2-day and 10-day cycles the recovery was practically equal to the flow; hence the residual deformation exhibited in the figures was due to the fact that on the average the instantaneous recoveries were less than the instantaneous deformations.

TESTS OF SERIES VII

Conditions:

The purpose of these tests was to determine the effect of flow upon the compressive strength and modulus of elasticity. That is, it was desired to learn how these properties of a concrete which had been subjected to sustained stress for a considerable period of time would compare with those of an identical concrete not previously stressed. The tests were begun in October, 1929, and are still in progress.

The specimens were 6 by 12-in. cylinders, 64 in number, half of which were placed under continuous load at 28 days and the remainder of which were not stressed prior to the strength test.

Two concrete mixes were employed, a rich mix composed of 1 part of cement to 3.6 parts by volume of combined aggregate, and a lean mix composed of 1 part of cement to 6.3 parts of combined aggregate. The mix data are given below. For the rich mix, the fineness modulus of the combined aggregate was 5.70 and the water-cement ratio 0.71. For the lean mix the fineness modulus of the combined aggregate was 5.55 and the water-cement ratio was 0.99. For both mixes the slump was 3 to 4 in.

	PARTS BY WEIGHT				
CEMENT-AGGREGATE, RATIO BY VOLUME	CEMENT	MONTEREY SAND	TOP GRAVEL	MEDIUM GRAVEL	COARSE GRAVEL
1:3.6..............	1	0.66	0.66	1.34	1.34
1:6.3..............	1	1.26	1.26	2.24	2.24
Fineness Modulus..	..	2.15	2.92	6.88	7.63

For the first 7 days all specimens were fog cured. Thereafter half of the specimens were stored under water and the remainder were stored in air at 50 per cent relative humidity. At 28 days, half of those stored in both air and water were loaded to 800 lb. per sq. in. The remainder, as noted above, were left unstressed.

The tests here considered, on half the total number of specimens, are for concrete at an age of 5 months, with a sustained loading period of 4 months. (The remaining specimens are being held for testing at the age of 12 months when the period of sustained load will have been 11 months.) At the end of the period of sustained stress the load was removed from a specimen, observations of instantaneous recovery were made, and as quickly as possible thereafter the specimen was loaded in a testing machine to failure, measurements of deformation being made with a compressometer as the load progressed. At the same time, corresponding unstressed or control specimens were likewise tested to failure.

Results:

Figure 12 shows graphically the relation between flow and time for the specimens of series VII. For dry storage the effect of richness of mix is seen to be pronounced. Here, as among preceding series, the moisture conditions of storage exert a profound influence upon flow. For the dry group at 120 days after loading the specimens of the 1:3.6 mix had deformed about two-thirds as much as those of the 1:6.3 mix.

In Fig. 13 are shown the stress-strain diagrams for both dry and wet storage and for both lean and rich mixes, each curve representing the average of 4 specimens. The full lines give the stress-strain relation for specimens not previously loaded, and the dash lines similarly indicate the behavior of specimens which had been subjected to sustained stress. Comparing the diagrams, it will be found that:

1. The instantaneous deformation for any stress is less for concrete previously subjected to a sustained load than for one not so treated. This, of course, is to be expected, since the previously loaded specimens, tested immediately after being released from sustained load already were considerably deformed due to the time effect.

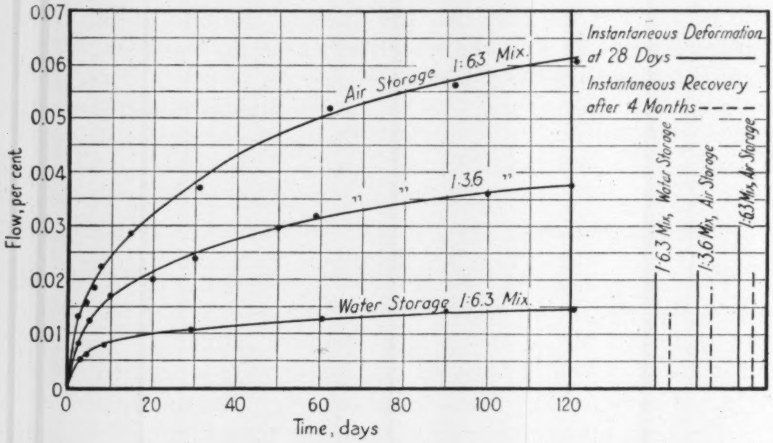

FIG. 12.—Effect of Richness of Mix and Storage Upon Flow, Series VII.

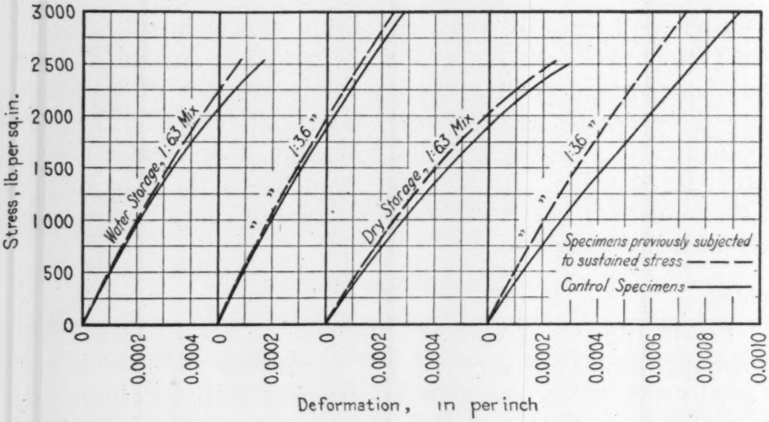

FIG. 13.—Effect of Sustained Load Upon Stress-Strain Relation, Series VII.

2. The stress-strain ratio, both for previously stressed and unstressed specimens is higher for a concrete when wet than for the same concrete when dry.

3. The stress-strain ratio both for previously stressed and unstressed specimens is higher for concrete of rich mix than for similar concrete of lean mix.

4. For the wet concrete, the stress-strain ratio within the limits of working stresses is substantially the same for specimens which have been previously subjected to sustained load as it is for specimens not previously stressed; but for concrete in dry storage this is not true, the specimens previously under sustained load exhibiting a materially higher modulus of elasticity even at low stresses.

The compressive strengths of both rich and lean mixes for both air and water storage are given below:

	RICH MIX, 1:3.6		LEAN MIX, 1:6.3	
STORAGE	LOADED	CONTROL	LOADED	CONTROL
Air	5505	5610	3260	3245
Water	6213	6010	3460	3560

An examination of the table shows remarkably close agreement between the unstressed control specimens and the corresponding specimens which had been subjected to sustained load prior to the test. There is no consistent variation and the differences between corresponding values are no greater than would normally be expected between two groups of identical specimens. Thus it appears that within the limits of these tests, the compressive strength of concrete is unaffected by flow.

SUMMARY OF CONCLUSIONS

Studying the results of these investigations it appears that all concretes, subjected to compressive stress, flow for a considerable period of time, regardless of the age at the time of loading, magnitude of sustained stress, character of aggregate, richness of mix, and storage conditions. It is seen that frequently the flow which takes place subsequent to the application of load is of a magnitude considerably greater—in some cases several times greater—than the deformation which takes place immediately upon application of the load. It is worth observing that there is no evidence of flow having ceased in any of the specimens in dry storage, though a considerable number of the specimens have been continuously stressed over a period of more than three years and though it appear that at the lower stresses the rate of or increase in flow, for concrete in dry storage as well as wet becomes comparatively small after two or three years.

It is also worth remarking that even comparatively minor variations in the humidity of the atmosphere are sufficient to alter the rate of flow.

The following conclusions pertain to the flow of concrete under sustained compressive stress:

1. Other things being equal, the flow of concrete is greater for a lean mix than for a rich one (see Fig. 1). The flow for a 1:7 mix after a period of sustained load under conditions of dry storage is more than twice as large as for a 1:4 mix under the same conditions of storage.

2. For the same richness of mix the flow is greater in a concrete for which the aggregate contains a large amount of fines (resulting in a higher water-cement ratio) than in a similar concrete for which the aggregate has less fines (resulting in a lower water-cement ratio) (see Fig. 1).

3. The character of the mineral aggregate has a marked influence upon flow. For the aggregates included in these tests, limestone concrete flows the least, while sandstone and basalt concretes flow the most. Granite and quartz concretes exhibit flows of intermediate magnitude (see Fig. 7).

4. The flow is materially influenced by the moisture conditions, surrounding the concrete. In general the drier the conditions of storage the greater the deformation in a given concrete (see Figs. 3, 4, 5, and 6). The flow taking place during one year of sustained load on concrete stored in water, stored in air at 70 per cent relative humidity and stored in air at 50 per cent relative humidity, are roughly in the proportions of 1:2.4:3 (see Fig. 6).

5. Other things being equal, the greater the age at the time of applying the sustained load, the less the flow (see Figs. 2, 3, 4 and 5).

6. Other things being equal, the higher the sustained stress the larger the flow which takes place during a given interval of time (see Figs. 2, 3, 4 and 5).

7. Compressive reinforcement acts materially to reduce flow (see Fig. 8). Likewise compressive reinforcement acts materially to reduce shrinkage (see Fig. 8). For the tests here considered, for which the longitudinal reinforcement amounted to 1.90 per cent of the full cross-sectional area of the cylinder, the reinforced specimen exhibited a flow approximately three-fifths that of the plain specimen. The same ratio obtained in the case of shrinkage.

8. For the tests here considered the increase of stress in the steel during the period of flow is large. The cumulative effect of flow and shrinkage increased the stress in the steel from 5600 lb. per sq. in. at the beginning of the period of sustained load to 25,800 lb. per sq. in. after approximately 8 months of sustained load. About one-half of this increase was due to shrinkage and about one-half was due to flow.

9. Some of the maximum values of flow in terms of inches per 100 ft. follow (see Figs. 1, 5, 6, 7, 8, and 12):

Series I.—0.6 in. per 100 ft. under a compressive stress of 640 lb. per sq. in. for a period of 5 months. The mix was 1:7 and the water-cement ratio was 1.42.

Series II.—1.6 in. per 100 ft. after 3 years of sustained load at a stress of 1200 lb. per sq. in., load having been applied at the age of 3 months and the specimens having been in dry storage.

Series III.—0.9 in. per 100 ft. after one year of sustained load at a stress of 800 lb. per sq. in. in dry storage.

Series IV.—1.3 in. per 100 ft. after 1 year of sustained load at a stress of 800 lb. per sq. in., the aggregate being sandstone.

Series V.—0.6 in. per 100 ft. after 8 months of sustained load at 800 lb. per sq. in., the specimen being plain concrete.

Series VI.—0.7 in. per 100 ft. after 4 months of sustained load at 800 lb. per sq. in. on a 1:6.3 mix.

10. When concrete is subjected to a cyclic repetition of constant sustained stresses, there is left in the concrete a residual deformation which is not unlike the simple flow in its rate of increase with number of cycles. This residual deformation is due to both the excess of time flow over time recovery and instantaneous deformation over instantaneous recovery. There is also a permanent set which takes place at the time of first application of load (see Figs. 9, 10 and 11).

11. The residual deformation in concrete subjected to a series of stress cycles is influenced by the factors which influence the simple time-deformation or flow, for example, moisture conditions, age, etc.

12. The residual deformation in concrete subjected to a series of stress cycles is roughly independent of the period of the cycles.

13. The instantaneous modulus of resistance or modulus of elasticity of a concrete which has been subjected to a sustained stress is higher than that for the same quality of concrete not previously stressed (see Fig. 13).

14. Apparently the concrete which has been subjected to sustained stress exhibits the same compressive strength as concrete of the same quality which has not been previously stressed (see results of tests of series VII). In other words, the magnitude of the deformation prior to the application of the load producing failure has no effect upon the compressive strength. (This should not be confused with fatigue effects due to repetition of stress.)

15. The modulus of elasticity of concrete, as determined by the ratio of unit stress to unit deformation at the time of application of load, taken by itself is no criterion of the flow that may be expected

to take place during a given interval of time (see Figs. 2, 3, 4, 5, 6, 7, 8 and 12). Apparently the character of the mineral aggregate has a much more marked influence upon the flow of concrete than upon the instantaneous modulus of elasticity.

Acknowledgment.—The tests described herein were conducted in the Materials Testing Laboratory of the University of California. The funds for carrying on the work were derived partly from grants of the Research Board of the University of California, partly from donations received from the Committee on Arch Dam Investigation of Engineering Foundation, and partly by appropriation of the American Society of Civil Engineers through its Committee on Arches.

Though numerous persons have contributed their services at one time or another, it is desired to acknowledge in particular the assistance rendered by Mr. G. E. Troxell, Assistant Professor of Civil Engineering, who supervised many of the earlier tests, and Mr. J. L. Banville, Assistant in the Materials Testing Laboratory, who has been immediately in charge of much of the work since the beginning and who is in a large measure responsible for the design of special instruments and apparatus used.

VARIATIONS OF COMPRESSIVE STRENGTH OF CONCRETE WITHIN THE WATER-CEMENT RATIO LAW

By Ira L. Collier[1]

Synopsis

The paper describes three series of concrete tests covering 450 specimens, carried out by a class of students at the University of Washington. It is a matter of observation that the curves having the same water-cement ratio and using the same cement do not have equal strength and the three series of tests were designed to study (1) effects of various consistencies, (2) effect of various percentages of sand, (3) effect of various gradings of sand, in concrete having a number of different water-cement ratios.

The tests show that the compressive strength of concrete of the same water-cement ratio decreases as the slump increases, in general decreases as the percentage of sand is decreased, and decreases as the fineness modulus of the sand is increased.

The explanation for this is advanced that the factors above enumerated control the condition of the cement paste at the time the hardening process begins and it is the relationship of the cement and water at this time that determines the strength of the concrete.

Introduction

Why does not all concrete having the same water-cement ratio and using the same cement have equal strength? The wide variation occurring is shown in Fig. 1, plotted from data supplied by the Portland Cement Association, Series 78, 83 and 85. Most of the points fall in a zone approximately 1500 lb. per sq. in. in width. However, points are found even beyond these limits.

The reasons for this variation in strength are indicated by data gathered during the past few years by students in classes in materials of construction conducted by the author at the University of Washington.

Three different series of tests were performed, to determine, if possible, how the strength of concrete is affected by variation in consistency of mix, and in proportion and grading of the sand. Figure 2 shows the water-cement ratio - strength curves for the three series. All tests were conducted in the standard manner, except that the specimens were not made by one individual. Each of the four (in some cases only three) specimens obtained under like conditions was made by a different group of students. The variation in strength,

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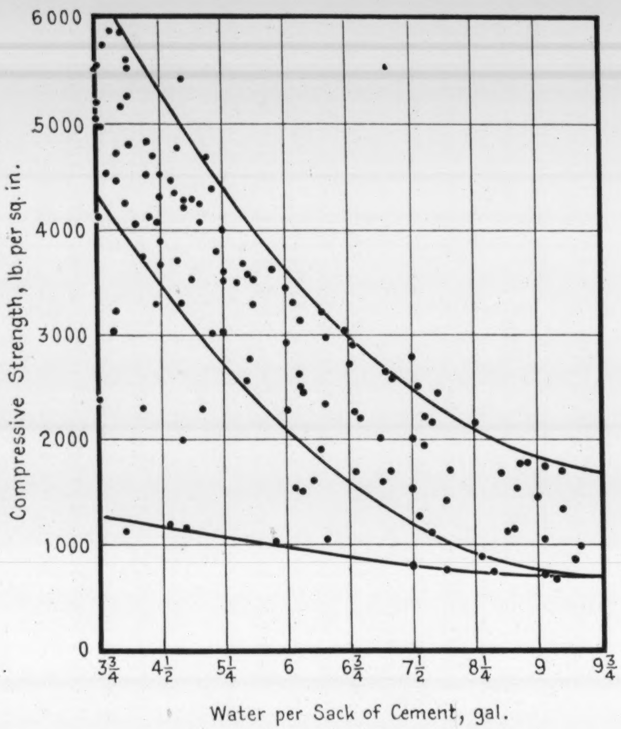

FIG. 1.—Water-Cement Ratio - Strength Relation.

Data supplied by the Portland Cement Association, Series 78, 83 and 85.

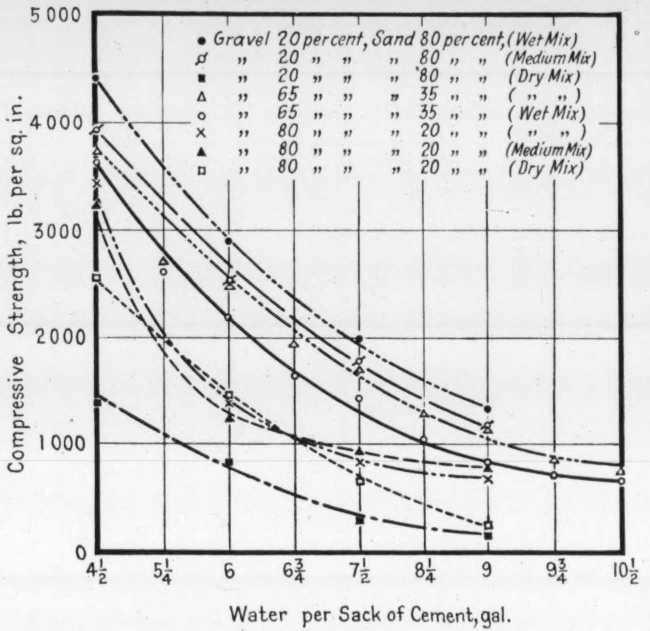

FIG. 2.—Water-Cement Ratio - Strength Relation.

Data taken at the University of Washington.

however, between the four test specimens was no greater than if the specimens had been made by one individual.

SERIES 1. EFFECT OF VARIOUS CONSISTENCIES ON STRENGTH

Object.—To find the strength of concrete having various consistencies, but with the water-cement ratio constant.

TABLE I.—RESULTS OF TESTS, SERIES 1.

Water-Cement Ratio, $\frac{W}{C}$	Paste, lb.	Slump, in.	Proportions, per cent		Volume of Concrete, cu. ft.	Weight of Concrete, lb. per cu. ft.	Compressive Strength, lb. per sq. in.
			Sand	Gravel			
0.6	14	1	35	65	0.258	148	3710
	15	3			0.265	150	3680
	16	5			0.270	150	3400
	17	7			0.287	149	3620
	18	9			0.285	146	3620
0.7	6.5	1	35	65	0.211	155	2690
	7.0	3			0.215	153	2890
	7.5	5			0.217	155	2650
	8.0	7			0.221	154	2460
	8.5	9			0.224	153	2680
0.8	5.9	1	35	65	0.211	152	2510
	6.8	3			0.212	152	2290
	7.7	5			0.221	154	2360
	8.6	7			0.224	152	2360
	9.5	9			0.241	152	2100
0.9	4.6	1	35	65	0.202	154	1940
	5.8	3			0.207	153	1670
	7.0	5			0.220	153	1840
	8.2	7			0.221	153	1740
	9.4	9			0.230	152	1580
1.0	4.3	1	35	65	0.200	152	1650
	5.2	4			0.202	154	1620
	6.1	6			0.210	154	1480
	7.0	9			0.210	153	1390
1.1	3.9	1	35	65	0.201	150	1270
	4.8	4			0.201	150	1160
	5.7	6			0.213	152	1070
	6.6	9			0.209	149	1070
1.2	3.7	1	35	65	0.200	152	900
	4.4	4			0.200	152	993
	5.1	6			0.201	153	945
	5.8	9			0.208	152	790
1.3	3.5	1	35	65	0.200	151	880
	4.2	4			0.200	151	790
	4.9	6			0.206	151	760
	5.6	9			0.210	151	680
1.4	3.5	1	35	65	0.198	151	780
	4.3	4			0.200	151	720
	5.1	6			0.204	152	700
	5.9	9			0.208	152	650

Variable Factors.—The consistency was varied from a dry mix with approximately 1-in. slump, to a wet mix with 9-in. slump. The tests were made nine times, a different water-cement ratio being used for each set.

Constant Factors were grading of sand and gravel (the grading was about the same as that of the sand and gravel found on the

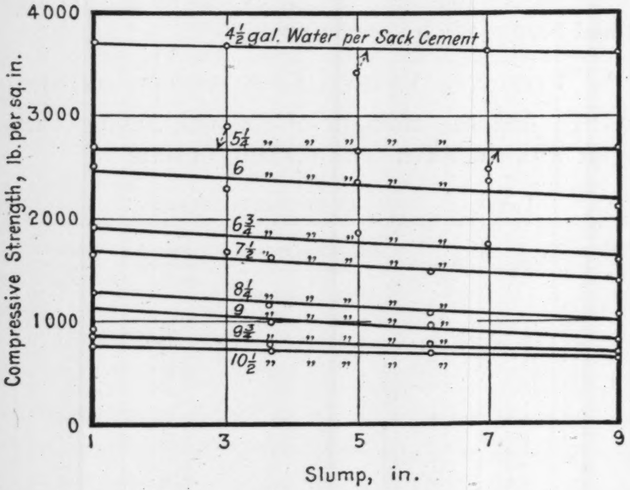

FIG. 3.—Tests of Series 1, Showing the Effect of Variable Consistencies with Constant Water-Cement Ratio.

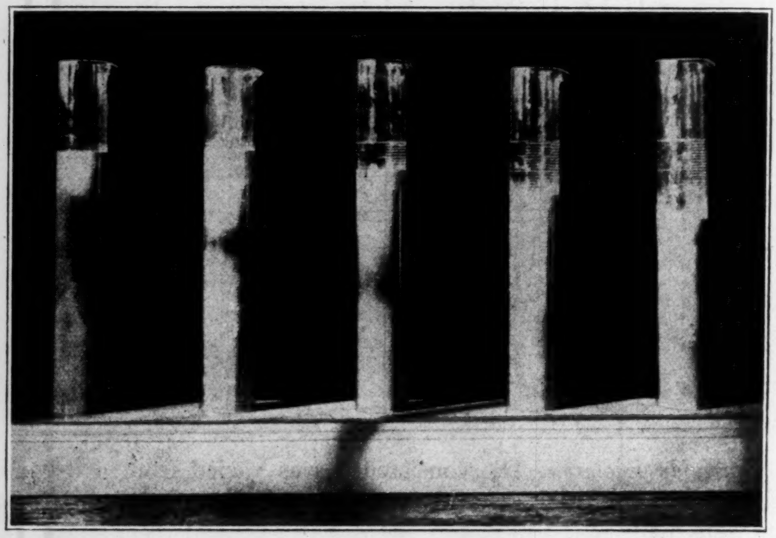

FIG. 4.—Shows How Cement Settles from Various Cement Pastes.

Seattle market), percentage of sand and gravel (35 and 65 per cent, respectively), water-cement ratio for each set, and quality of cement.

TABLE II.—RESULTS OF TESTS, SERIES 2.

Water-Cement Ratio, $\frac{W}{C}$	Paste, lb.	Slump, in.	Proportions, per cent		Volume of Concrete, cu. ft.	Weight of Concrete, lb. per cu. ft.	Compressive Strength, lb. per sq. in.
			Sand	Gravel			
0.6	5.1	0	20	80	0.215	149	2540
	6.5	0	35	65	0.217	154	3860
	7.9	0	50	50	0.232	150	3700
	9.3	0	65	35	0.246	144	2840
	10.7	0	80	20	0.266	140	1353
0.6	7.7	4	20	80	0.218	155	3240
	9.5	5	35	65	0.239	153	3680
	11.3	4	50	50	0.252	151	3690
	13.1	4	65	35	0.266	149	3890
	14.9	4	80	20	0.284	147	3930
0.6	10.2	9	20	80	0.229	155	3380
	12.4	9	35	65	0.254	153	3600
	14.6	9	60	50	0.272	149	3680
	16.8	9	65	35	0.289	147	4040
	19.0	9	80	20	0.303	146	4370
0.8	4.4	0	20	80	0.216	152	1440
	4.9	0	35	65	0.206	152	2370
	5.4	0	50	50	0.216	151	2120
	5.9	0	65	35	0.230	143	1340
	6.4	0	80	20	0.242	140	970
0.8	5.6	3	20	80	0.208	154	1270
	6.6	3	35	65	0.212	154	2170
	7.6	3	50	50	0.228	151	2500
	8.6	3	65	35	0.241	149	2450
	9.6	3	80	20	0.253	147	....
0.8	6.8	9	20	80	0.206	154	1400
	8.2	9	35	65	0.226	152	1980
	9.6	9	50	50	0.236	151	2470
	11.0	9	65	35	0.250	149	2680
	12.4	9	80	20	0.264	149	2880
1.0	4.4	3	20	80	0.208	151	920
	5.5	3	35	65	0.209	154	1300
	6.6	3	50	50	0.219	150	1730
	7.7	3	65	35	0.229	146	1720
	8.8	3	80	20	0.238	143	1760
1.0	6.3	9	20	80	0.208	152	850
	7.6	9	35	65	0.223	150	930
	8.9	9	50	50	0.238	149	1320
	10.2	9	65	35	0.246	148	1820
	11.5	9	80	20	0.258	144	1970
1.2	3.8	3	20	80	0.208	149	770
	4.6	3	35	65	0.202	154	990
	5.4	3	50	50	0.213	150	1300
	6.2	3	65	35	0.228	147	1350
	7.0	3	80	20	0.231	141	1140
1.2	5.5	9	20	80	0.204	153	640
	6.8	9	35	65	0.216	152	760
	8.1	9	50	50	0.232	150	1010
	9.4	9	65	35	0.250	147	1250
	10.7	9	80	20	0.261	144	1330

Test Procedure.—Each party, consisting of two students, weighed out the given quantity of the various-sized aggregate. Then they mixed cement and water in the given ratio. To the mixed aggregate they added enough of the cement paste to produce the desired con-

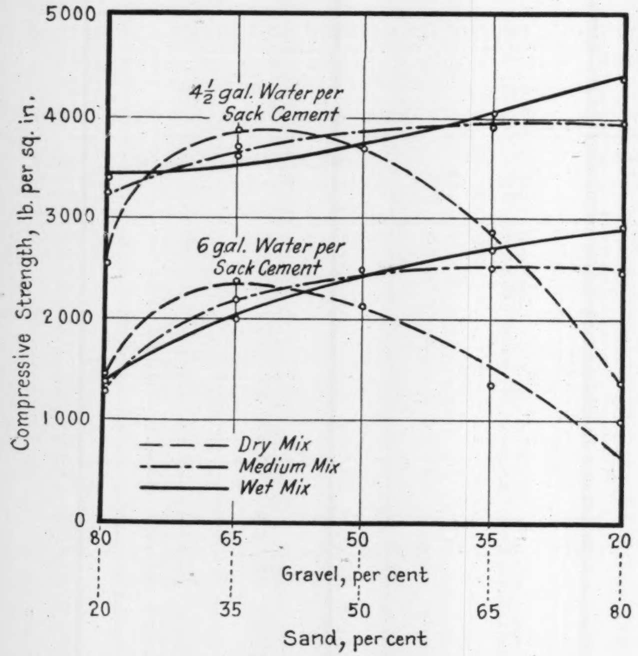

FIG. 5.—Tests of Series 2, Showing the Effect of Various Proportions of Sand and Gravel, Constant Water-Cement Ratio.

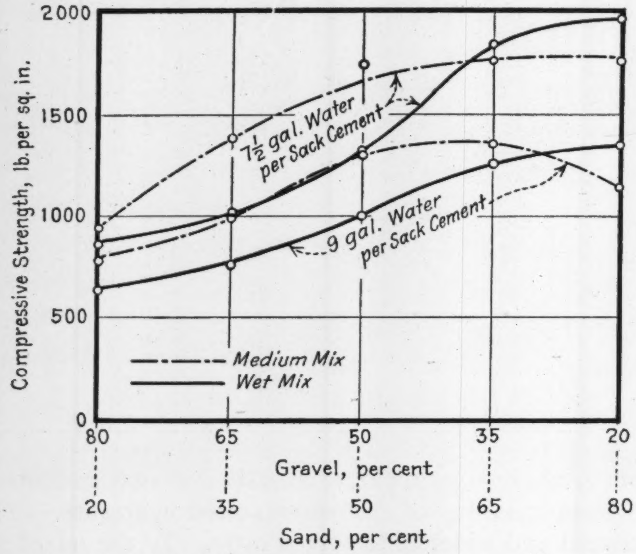

FIG. 6.—Tests of Series 2, Showing the Effect of Various Proportions of Sand and Gravel, Constant Water-Cement Ratio.

sistency. As storage space was limited, all specimens were tested at 7 days.

The results of the first series are given in Table I and in Fig. 3. In all cases the strength for the 9-in. slump is less than that for the 1-in. slump. The strength is actually less in the specimens that contained a higher amount of cement. All strengths in these series are high for a 7-day test; however, this is a condition that exists for the particular brand of cement used.

Figure 4 shows five graduated cylinders filled to the 500-cc. mark with cement paste. Beginning at the left, they contained paste made in the following ratios: 0.6, 0.8, 1.0, 1.2 and 1.4. The manner in which the cement settled out is shown clearly.

An explanation for the results of the first series, which applies as well to the other two series, is as follows: The sand in the specimens can hold, by capillarity, only a certain amount of cement paste in a homogeneous condition. If an excessive amount of paste is added, the water and the cement in the different layers of paste surrounding the pieces of aggregate separate exactly as shown in Fig. 4. The cement settles on the tops of the stones, resulting in a strong mortar matrix, and a film of water remains about the under sides, giving a very poor bond at these points. Concrete, like the proverbial chain, is as strong as its weakest link.

SERIES 2. EFFECT OF VARIOUS PERCENTAGES OF SAND ON STRENGTH

Object.—To find the strength of concrete having various percentages of sand.

Variable Factors.—Five different sand contents, two consistencies, and four water-cement ratios.

Constant Factors are grading of sand and gravel (same as in Series 1), water-cement ratio for each set, and quality of cement.

Test Procedure.—As in Series 1.

The results of Series 2 are given in Table II and in Figs. 5 and 6. The most outstanding feature is the very large increase in strength in the over-sanded mixes compared to the under-sanded mixes or compared to the normal mix. An explanation is that the increased quantity of sand requires more paste to produce the same consistency. This larger amount of sand can hold a greater amount of paste in a uniform condition without the cement settling from the paste. The increased amount of paste is not in itself an explanation for this increase in strength, because both series of tests show that for the lower sanded mixes the strength is less in the specimens containing the larger amount of paste.

SERIES 3. EFFECT OF VARIOUS GRADINGS OF SAND ON STRENGTH

Object.—To find the strength of concrete having various gradings of sand.

Variable Factors.—Five different gradings of sand (Fig. 7 shows the mechanical analysis curves for the five sands), two consistencies, and four percentages of sand.

Constant Factors are water-cement ratio ($7\frac{1}{2}$ gal. of water per sack of cement), grading of gravel and quality of cement.

Procedure.—As in Series 1.

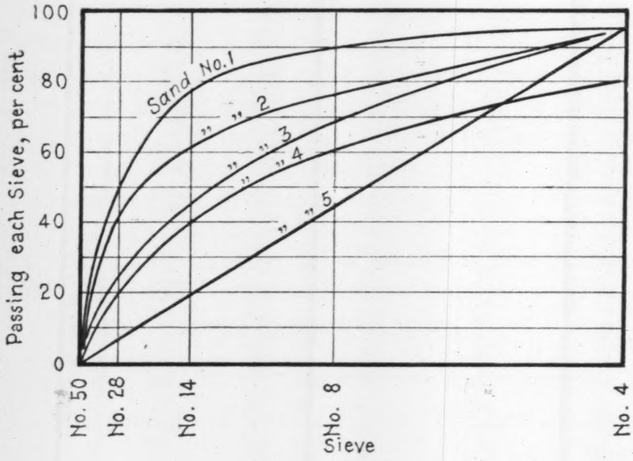

FIG. 7.—Mechanical Analysis Curves of Five Sands Used in Series 3.

The results of Series 3 are given in Table III and in Figs. 8 and 9. The maximum strength, 2000 lb. per sq. in., was obtained with sand No. 1, wet consistency, 9-in. slump, 80 per cent sand and 20 per cent gravel. Minimum strength, 280 lb. per sq. in., was obtained with sand No. 5, medium consistency, 4-in. slump, 20 per cent sand and 80 per cent gravel. In the under-sanded mixes, 20–80, and for the coarser sands, the strength depends on the quantity of paste, as the wet mixes are stronger for all five sands than the medium mixes. The medium mixes do not have sufficient paste to fill the voids. In the mix containing 35 per cent sand and 65 per cent gravel, the strength is greater for the medium consistencies for sands Nos. 1, 2 and 3, equal for sand No. 4, and weaker for sand No. 5. Here, as is shown in the other two series, the strength is not a function of the quantity of paste for any one sand, except for the coarse sand No. 5.

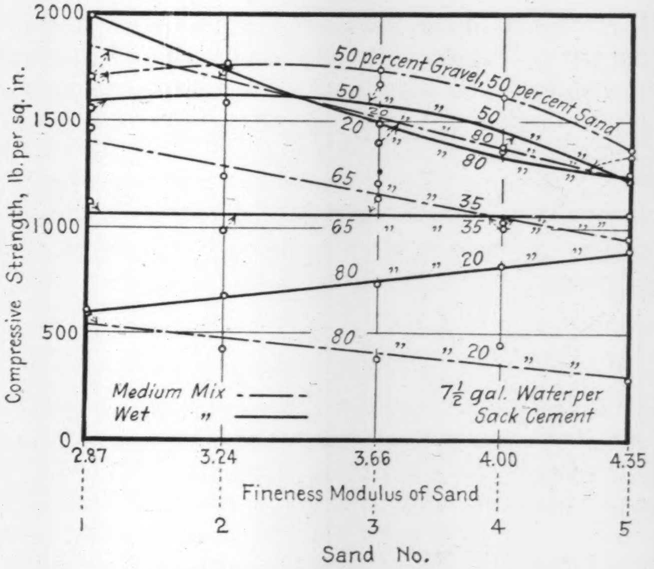

FIG. 8.—Tests of Series 3, Showing the Effect of Various Gradings of Sand, Constant Water-Cement Ratio.

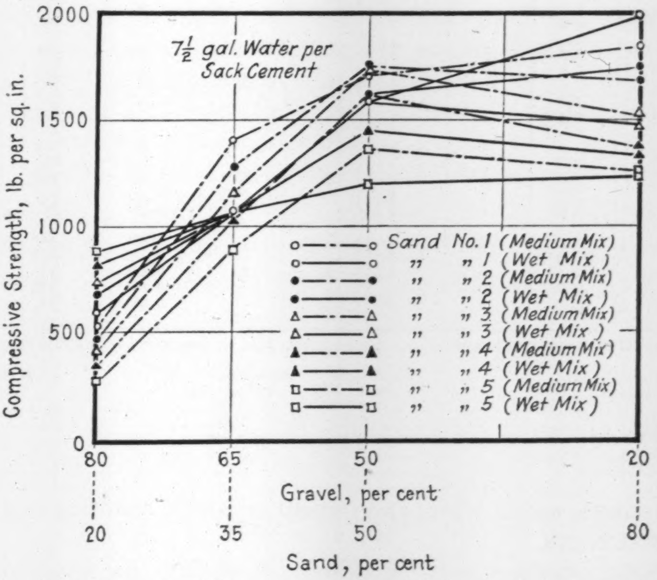

FIG. 9.—Tests of Series 3, Showing the Effect of Various Gradings of Sand and Various Proportions of Sand and Gravel, Constant Water-Cement Ratio.

Instead, it depends upon the quality of the paste at the time the hardening process begins. The finer sands hold a larger quantity of paste in a uniform condition, and hence a stronger concrete results.

TABLE III.—RESULTS OF TESTS, SERIES 3.

Water-Cement Ratio, $\frac{W}{C}$	Paste, lb.	Slump, in.	Sand	Proportions, per cent		Volume of Concrete, cu. ft.	Weight of Concrete, lb. per cu. ft.	Compressive Strength, lb. per sq. in.
				Sand	Gravel			
1.0........	3.5	4	No. 1	20	80	0.213	143	600
	2.9	4	No. 2			0.214	140	430
	2.8	4	No. 3			0.221	137	380
	2.8	4	No. 4			0.222	136	440
	2.7	4	No. 5			0.224	133	280
1.0........	5.5	10	No. 1	20	80	0.204	155	660
	5.0	10	No. 2			0.207	154	670
	5.0	10	No. 3			0.218	153	740
	5.1	10	No. 4			0.219	152	820
	4.7	10	No. 5			0.221	148	878
1.0........	5.8	4	No. 1	35	65	0.210	150	1460
	5.8	4	No. 2			0.208	150	1235
	5.6	4	No. 3			0.206	153	1210
	4.5	4	No. 4			0.207	151	1010
	4.0	4	No. 5			0.211	148	940
1.0........	7.0	10	No. 1	35	65	0.220	150	1110
	6.4	10	No. 2			0.219	152	980
	6.4	10	No. 3			0.214	153	1140
	5.9	10	No. 4			0.212	152	1020
	5.6	10	No. 5			0.208	153	1050
1.0........	7.3	4	No. 1	50	50	0.224	148	1720
	6.4	4	No. 2			0.218	148	1750
	6.2	4	No. 3			0.220	150	1740
	5.3	4	No. 4			0.207	151	1620
	5.7	4	No. 5			0.211	152	1370
1.0........	8.5	10	No. 1	50	50	0.236	148	1560
	7.7	10	No. 2			0.236	149	1590
	7.8	10	No. 3			0.231	150	1680
	7.2	10	No. 4			0.227	150	1370
	6.6	10	No. 5			0.219	151	1340
1.0........	11.0	4	No. 1	80	20	0.267	139	1710
	9.8	4	No. 2			0.260	141	1760
	8.5	4	No. 3			0.245	142	1400
	7.3	4	No. 4			0.236	144	1380
	6.0	4	No. 5			0.226	144	1250
1.0........	14.2	10	No. 1	80	20	0.306	141	2000
	11.8	10	No. 2			0.272	142	1770
	10.5	10	No. 3			0.262	143	1480
	9.2	10	No. 4			0.249	145	1360
	10.0	10	No. 5			0.253	147	1235

NOTE.—27 lb. of aggregate in each batch. Aggregate very hard, no correction for absorption necessary.

Cement per Pound of Paste, lb.	Water-Cement Ratio, W/C	Cement per Pound of Paste, lb.	Water-Cement Ratio, W/C
0.715	0.6	0.578	1.1
0.681	0.7	0.556	1.2
0.651	0.8	0.536	1.3
0.625	0.9	0.518	1.4
0.600	1.0		

In the coarse sands, water and cement separate, resulting in a concrete of low strength.

Some question may be raised concerning the water coming to the top of the wet specimens containing a large percentage of fine sand and made from thin pastes. It is true that some liquid comes to the surface; however, it is not water but cement paste. The cement then settles out, leaving a layer of water. It is also true that this liquid, working its way to the surface, is probably not of the same composition as the paste of which the specimen was made. Hardly could a uniform quantity of water be withdrawn from all portions of the specimen in such a manner that it could be said that a new and thicker paste has been substituted for the original one. Therefore, there is no justification for the idea that this water coming to the surface should be subtracted from the water content of the entire specimen and a new water-cement ratio computed.

CONCLUSIONS

These tests have demonstrated that if the water-cement ratio of concrete is held constant and the sand and gravel are in the usual proportions of 1:2, the compressive strength decreases as slump increases, in general decreases as the percentage of sand is decreased, and decreases as the fineness modulus of the sand is increased.

The following explanation of these changes in strength with constant water-cement ratio is advanced: The sand in a concrete can hold only a certain amount of cement paste in a homogeneous condition. If any amount over this is used, the cement and water tend to separate before the hardening begins, resulting in a loss of strength, hence the condition of the cement paste at the time the hardening process begins is determined by the factors that have been studied, and it is the relationship of the cement and water at this time that governs the strength of the concrete.

DISCUSSION

MR. R. L. BERTIN.[1]—I should like to ask Mr. Collier whether all the mixes used in these tests were within the limitations of the water-cement ratio law?

MR. I. L. COLLIER.[2]—As we are trying to discover the principle involved, we must go from extreme to extreme. We cannot call 80 per cent gravel, 20 per cent sand a plastic mix, but if we are trying to discover underlying principles we must go from one extreme to the other, so I have covered a wide range.

MR. H. F. GONNERMAN.[3]—There are a few points that occurred to me in reading Mr. Collier's paper. Figure 3 gives certain relationships between the strength of concrete of a given water-cement ratio as indicated by the gallons per sack and the slump. A study of the data in Table I from which this figure was plotted shows that a slight change in the strength of the concrete of 1-in. slump in each of the groups of tests would change the position of the curves on the diagram. It is possible when the students made the specimens for which a slump of 1-in. is recorded that they rodded them somewhat more than the others and the strengths are therefore somewhat higher. If these particular points were disregarded, the curves could be rotated so that they would be more nearly horizontal than shown on the diagram.

In the next group of tests plotted in Figs. 5 and 6, the consistency called "dry mix" had zero slump. When concrete of zero slump is molded by the standard A.S.T.M. method, one can get most any strength desired, depending on how the concrete is placed in the mold. With such dry mixes and large variations in the percentage of sand of from 20 to 80 per cent, a large variation in the resulting concrete placed according to these particular methods would be expected. This, I think, is the reason why the dash line curves show such a marked difference from the solid line curves which represent the workable mixes.

Another point to be considered is the segregation of the water from the concrete after it is placed in the mold. The statement is made that the aggregates were very hard and no correction for absorption was necessary. That being the case with the harsh mixes, considerable segregation of the mixing water from the concrete would be expected, and I was wondering if an attempt had been made to collect the segregated mixing water and determine the water-cement ratios obtaining in the hardened concrete? We have done this in some of our work and have found that by measuring the segregated water and correcting the water-cement ratio accordingly that the plotted points agree closely with the type of curve presented in our various publications.

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[1] Chief Engineer, White Construction Co., Inc., New York City.

[2] Assistant Professor of Civil Engineering, University of Washington, Seattle, Wash.

[3] Manager, Research Laboratory, Portland Cement Assn., Chicago, Ill.

Figure 1 of the paper contains data from Series 78, 83 and 85 made at the Structural Materials Research Laboratory, Lewis Institute. As I recall, these series were made about 1916 to 1918 when Mr. Abrams was studying the general relationship between the quantity of mixing water and compressive strength of concrete. In that study he used a wide range of mixes, many of which would not be considered workable when judged by present-day standards. If the mixes plotted in this figure were studied more closely so as to determine whether or not they were workable and the unworkable mixes eliminated, one would get a better picture of the data shown in this particular figure.

In making studies of the water-cement ratio - strength relationship, we must take into account the condition of the concrete as placed in the mold and also what happens after it is placed in the mold. If segregation of the mixing water occurs, corrections must be made. I should like to ask Mr. Collier if he attempted to measure the water which segregated from the concrete in these experiments?

MR. COLLIER.—No, sir.

MR. GONNERMAN.—The different sets of data, I understand, were obtained by different groups of students?

MR. COLLIER.—Yes, sir.

MR. GONNERMAN.—In the same year or different years?

MR. COLLIER.—All right together, on the same day.

MR. GONNERMAN.—And the variation was no greater than if made by one operator?

MR. COLLIER.—No, sir.

MR. GONNERMAN.—It would be helpful to have some indication of the extent of the variations in the individual results.

MR. COLLIER.—It was about the same as we expect in any of our tests.

MR. GONNERMAN.—Were absorption tests made on the aggregate?

MR. COLLIER.—I have at times, the same aggregate was used at all times and we found no absorption.

MR. GONNERMAN.—But would you not get considerable segregation with the coarser sands?

MR. COLLIER.—No attempt was made to measure the amount of water leaking from the molds or that which came to the surface. Undoubtedly more leaked from some than from others.

MR. GONNERMAN.—Would water not accumulate on the surface of the specimen?

MR. COLLIER.—In the ordinary concrete it would not; in the wetter mixes where they were oversanded, it would.

MR. GONNERMAN.—It would seem that in the case of the coarser sands where the mixtures were undersanded, there would be considerable segregation.

MR. COLLIER.—In regard to Series 1, other tests also indicate that a 9-in. slump gives a decrease in strength. In fact, the Portland Cement Association recommends applying the water-cement ratio law only to plastic mixes of 3 to 4-in. slump and very little concrete as dry as this is used. Therefore one would infer that a concrete having a 9-in. slump with the same water-cement ratio would be inferior.

For a number of years past the engineers of the country have been told that concrete having the same water-cement ratio would have the same strength, regardless of other factors. Now they are told that the law applies only to plastic mixes and are not told what result might be expected if they failed to use such a mix.

In these tests of mine I have shown that the wetter mixes with 65 per cent gravel and 35 per cent sand are weaker and I have given an explanation for such difference.

In regard to the water leaking from the molds in Series 1, I think undoubtedly more water leaked from the molds in the 9-in. slump concrete than in the one inch. Therefore the water-cement ratio at the time of set was lowered and the strength should have increased, according to Mr. Gonnerman's theory, but it actually decreased.

Leakage of water from the mold cannot explain the increase in strength in the wet mixes because water leaked from all and if more water leaked from the oversanded than from the undersanded, it was because more paste was used in those mixes. Therefore, if it is desired to refer the data to the water-cement ratio in the hardened specimens and not to the ratio when the specimens were made, the figure must be $5\frac{3}{4}\pm$ gallons per sack of cement instead of 6 gallons per sack and none of the other relationships will be disturbed.

MR. GONNERMAN.—That depends on the grading of the materials. The only satisfactory way to solve this problem would be to determine the amount of water actually separated out of the concrete after placing. If some measure of that water were available one would be in a better position to interpret the data presented.

MR. COLLIER.—At the time I started the experiments I did not think of that. In no case have I seen a test in which the water which leaked out has been taken into consideration. As a rule we use the water-cement ratio entering the specimen; it would be difficult to tell what the water-cement ratio in the specimen is at the time the hardening process begins.

MR. GONNERMAN.—In 1929, Mr. T. C. Powers presented a paper before the American Concrete Institute on "Concrete Studies at the Bull Run Dam."[1] In discussion of this paper Mr. Lyse presented some data of tests made in our Laboratory covering the point under discussion. In these tests we found considerable segregation of mixing water from certain of the concrete mixtures. This was measured, and the water-cement ratios corrected for the water lost from the specimen. Had Mr. Collier attempted to measure the water which was lost from the various concretes he tested, it would have been easier to interpret the water-cement ratio curves presented in his paper.

MR. BERTIN.—I might say that the amount of water in the specimen after it had been placed in the mold could be determined by applying the segregation test described in the *Journal* of the American Concrete Institute for the months December and April, 1929.

MR. E. C. SHUMAN.[2]—I should like to ask Mr. Collier whether the concrete was struck off even with the top of the mold at the time of making the specimens or whether it was allowed to remain heaped for several hours and then struck off, the thought being, that if the concrete was heaped the water rising to the top would run off more readily than if the concrete had been struck off flat with the top of the mold.

MR. COLLIER.—The specimen was struck off, and if any water leaked out, the concrete naturally settled a little, so it would be below the top at the time the capping was made.

MR. H. J. GILKEY[3] (*by letter*).—This paper is so intimately related to matters that have been discussed by the writer in connection with the paper by Dwyer and Bates[4] and also Mr. McMillan's Appendix

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[1] *Proceedings*, Am. Concrete Inst., Vol. XXV, p. 388 (1929).

[2] Research Engineer, Koehring Division, National Equipment Corp., Milwaukee, Wis.

[3] Professor of Civil Engineering, University of Colorado, Boulder, Colo.

[4] J. R. Dwyer and P. H. Bates, "The Relation Between the Strengths of Cements Developed by Mortar Specimens and Concrete Specimens," see p. 598.

III to the Report of Committee C-9 on Concrete and Concrete Aggregates,[1] that the reader is referred to these two discussions for much of what might have been appropriately included here.

In the results from these tests, there is a remarkable agreement with results obtained in widely different manners by others. The Dwyer and Bates[2] tests, for example, give striking support to the conclusion that "at constant water-cement ratio the strength increases as the fineness of grading decreases," which is virtually what the author states in his second and third conclusions.

The evils of segregation from too great a fluidity have long been recognized as vital job problems from the standpoints of both placement and durability.[3, 4, 5, 6] From the standpoint of strength, overfluid mixtures (in comparison with stiffer mixtures of the same water-cement ratio) have received little attention in the laboratory other than that of a questionable sort[7] by Lyse[8] and by McMillan.[9] It is indeed reasonable that the increased segregation within a very fluid mass should weaken the resulting concrete. Series 1 of the paper is a quantitative measure of this. Eight to twenty-five per cent represents the strength reduction for a slump of from 1 to 9 in.

In Fig. 4 of McMillan's "Basic Principles of Concrete Making," much more striking evidence of what is probably the effect of high fluidity on a neat cement mixture is supplied. Referring to the accompanying Table I, the first two lines are taken from McMillan's upper curve (28-day strengths); the remaining lines are supplied by the writer as additional information. The total water-cement ratio range actually attainable for neat cement is probably included in the five left-hand columns of the table. That the strengths continued to fall off for mixtures having ratios of 5, 6, and 7.5 gal. per sack was due probably to enhanced segregation effects, rather than to any actual increase in the effective water-cement ratio.[1] Five gallons of water to the bag is slightly wetter than the 42 per cent by weight that was used in the fluid neat cement mixtures of the Tests on 32 cements by 47 laboratories reported by the Society's Committee C-1 on Cement in 1928[2] It is too wet to register on a slump test.

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[1] F. R. McMillan, Report of Committee C-9, Appendix III, "Suggested Procedure for Testing Concrete in Which the Aggregate Is More than One-Fourth the Diameter of the Cylinders," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 521 (1930).

[2] J. R. Dwyer and P. H. Bates, "The Relation Between the Strengths of Cements Developed by Mortar Specimens and Concrete Specimens," see p. 594.

[3] H. J. Gilkey, "Water Gain and Allied Phenomena," *Engineering News-Record*, February 10, 1927.

[4] H. F. Faulkner, "Impermeable Concrete for Permanence," *Western Construction News*, December 10, 1927, p. 48.

[5] F. R. McMillan, "Basic Principles of Concrete Making," McGraw-Hill Book Co., Inc., New York City, 1929; also *Engineering News-Record*, Vol. 102, January to July, 1929, pp. 580, 625, 673, 705, 748.

[6] R. B. Young, "The Requirements of a Durable Concrete as Observed from Structures in Service," *The Engineering Journal* (Canada), March, 1928.

[7] The question lies in the assumption that the water that gathers at the top of a fluid mixture is lost to the mixture and that the effective water-cement ratio has been thereby materially lowered. Barring leakage, evaporation, or removal, much of this water is drawn back into the specimen within a few hours. The strength of the specimen is not increased by the loss or removal of surface or other water unless greater compaction results. This is not normally the case. The shrinkage appears to be the same for a specimen in which the water is not drawn off as for one from which the surface water has been removed as it gathered. These matters are considered in more detail in the writer's discussion of the McMillan paper referred to previously.

[8] T. C. Powers, with Discussion by Lyse and others, "Concrete Studies at the Bull Run Dam," *Proceedings*, Am. Concrete Inst., Vol. XXV, pp. 423–425 (1929).

[9] F. R. McMillan, "Basic Principles of Concrete Making," p. 17, McGraw-Hill Book Co., Inc., 1929.

TABLE I.—PROBABLE EFFECT OF FLUIDITY ON COMPRESSIVE STRENGTH OF NEAT CEMENT.

Water-Cement Ratio, gal. per Sack of Cement	3	3.5	4	5	6	7.5
28-day Compressive Strength (from curve)	10 000	7600	5800	3750	2850	2000
28-day Compressive Strength (Abrams)	6 400	5630	4950	3810	2940	2000
Strength Ratio (Actual to Abrams)	1.56	1.35	1.18	0.98	0.97	1.00
Water-Cement Ratio, (Loose Volume, Abrams)	0.40	0.47	0.53	0.67	0.80	1.00
Water-Cement Ratio (per cent by weight)	26.6	31.1	35.5	44.4	53.3	66.6
Approximate Consistency	Stiff	Plastic	Wet	Cream	Light Oil	Skim Milk

The fourth line of the table gives the ratio of the actual strengths (as read from the curve) to Abrams "probable strength" as given by $S = \frac{14\,000}{7^x}$, and a regular and rapid decline is noted from 1.56 for the stiff mixture (about normal consistency in the standard tests) down to about 1.00 in the realm of the very wet neat cement mixtures. It seems reasonable that wet neat cement mixtures should undergo the sort of weakening segregation that Mr. McMillan's data appear to indicate. When a fluid mixture ceases to be agitated, a gravity sorting must start immediately, the larger or heavier particles of cement settling first and the finest last, with more compaction at the bottom.

Strangely enough, the data that the writer has used as a probable illustration supporting Mr. Collier's findings was used by Mr. McMillan as an illustration of how perfectly the Abrams relation holds for neat cement as well as for concrete, which only serves to show how varied are the deductions that can be made from a given set of data. If the curve for the $S = \frac{14\,000}{7^x}$ equation were plotted in Fig. 4 of McMillan's "Basic Principles," it would pass from tangency with the 28-day curve at 5 gal. per bag, cross the 10-day curve at 3.5 gal. and would join the 4-day curve at the left of the figure.

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[1] Beyond a certain limiting fluidity for any given mixture, the solids settle out and leave clear water at the surface (some of which may not return to the mixture), even though the mixture be kept quiet as long as it is in the liquid state. The solids in such a mixture have the greatest attainable dispersion or voids and the limiting value for effective water-cement ratio has been reached.

[2] Report of Subcommittee VII Committee C-1, on Strength: Report on "Cooperative Tests of Thirty-Two Portland Cements by Forty-Seven Laboratories," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part I, p. 261 (1928).

At a fixed water-cement ratio, there are but two ways that a given cement paste can be thickened:

1. More aggregate can be added,
2. A finer grading may be used.

In Series 1, Mr Collier has used the former expedient since his stiffer mixtures are the leaner ones and they are the stronger. The results when viewed in this light are very interesting. In some limited tests the writer has thought that he detected an opposite trend but he is willing to concede that there are strong indications that Mr. Collier's findings are the correct ones (up to some limiting leaneness of mix, perhaps). The Dwyer and Bates tests[1] (gradings B, F and I) do not appear to offer conclusive data on this phase of the subject. In case the extra aggregate added was at all absorptive, to that extent there could well be a lowering of the water-cement ratio in the leaner mixes.[2]

Series 2 parallels the tests of Dwyer and Bates for gradings K and L[1] in that the total aggregate was held constant but the grading was altered by successively changing the ratio of sand to gravel. The smaller gradings (larger sand contents) gave the higher strengths just as they did for Dwyer and Bates. It is natural that the paste had to increase with the sand content since it was the lubricating medium. Extra fineness gave increased surface areas to be coated.

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[1] J. R. Dwyer and P. H. Bates, "The Relation Between the Strengths of Cements Developed by Mortar Specimens and Concrete Specimens," see p. 594.

[2] Unless the absorption by the aggregate occurred during actual placement or while the particles were still in process of active readjustment, it should have but little effect because lowering the water-cement ratio is (for the most part, at least) effective only in so far as it serves to bring particles closer together (lower the dispersion, or decrease the voids). Most of the usual aggregates do accomplish the greater part of their absorption during the first few moments of immersion or of mixing and to whatever extent they are absorptive, to that extent the effective water-cement ratio is likely to be lowered.

Regarding the relationship of quantity of aggregate to quantity of paste, it is reasonable to suspect that, aside from the matter of relative stiffness and segregation effects, the quantity of aggregate present is not of great importance until some limiting value is attained, above which the paste supply is insufficient to coat all surfaces, even though the mixture be so well graded that there is no tendency toward harshness or honeycombing. Beyond this point the strength should fall off progressively as the aggregate is further increased. It is possible of course to obtain a very plastic workable mixture of sand without the addition of any cement.

The data of Table II of the paper (Series 2) could be rearranged at constant proportions and constant water-cement ratio to supply added comparisons of the effect of fluidity. That such a comparison fails to show the well-defined trend of Table I (Series 1) may be due to several factors that were less likely to be disturbing in Series 1:

1. With inexperienced assistance (students) some of the zero slump mixtures may not have had perfect placement.

2. The very harsh mixtures in which the stone-sand ratio was four might well have been honeycombed in some cases.

The following comments are offered relative to Table III, Series 3.

1. It shows a progressively decreasing strength as the grading of the sand becomes coarser.

2. As the sand-stone ratio increases (making the grading of the mixed aggregate finer) the strength consistently increases.

3. Probably the first two sets (stone-sand ratio of 4) are too harsh to supply valid data. The 10-in. slump mixtures are stronger than those with 4-in. slumps, but in such a harsh matrix, water that did decrease the effective water-cement ratio was no doubt lost in one way or another. It is unlikely that the coarse aggregate was really surrounded by a plastic matrix.

4. The four middle groups do supply evidence that agrees with Series 1, namely, that excess fluidity lowers the strength.

5. The last two groups offer mixed evidence on fluidity and no conclusion can be drawn from them on this score.

The writer's observations agree only in part with the remarks of the author, on page 741, relative to the water that gathers at the top of fluid mixtures. It is his observation that relatively little of the cement is brought to the surface by the water that rises. The writer feels that the effective water-cement ratio may be altered to whatever extent water is forced to the top by added compaction (decrease of voids or lowered dispersion of particles). The water that re-enters the mixture about the time that stiffening occurs is part of the effective water-cement ratio. Excessive working or tamping of over-wet or even plastic mixes can materially alter the effective water-cement ratio because added density is being obtained as the water is extracted. What is probably an excellent illustration of this is the apparent high strengths obtained from rodding in the well-known Texas rodded tests.[1]

The writer does not entirely agree with the author's explanation in his concluding paragraph since loss of water from the paste should make it more dense and therefore of better quality instead of weakening it. He does agree that paste in excess of that necessary to coat and hold the particles probably promotes gravity segregation and water gain on the under sides of aggregate particles. Moreover, as he mentions in discussion of the McMillan paper, he is inclined to believe that the initial break-down is a slippage between paste and aggregate and that the greater the relative area of contact surface for a given amount of aggregate (the finer the grading) the more firmly is the particle gripped. Thus the writer feels that the explanation is essentially a matter of (*a*) segregation (water gain, etc.)[1] and (*b*) relative surface areas in contact with the paste.

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[1] Texas Rodded Tests, Report of Committee C-9, Appendix II, Table IX, *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part I, pp. 339–340 (1922); also Report of Committee C-9, Appendix I, Table III, *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part I, p. 365 (1927).

At the present time, these minor differences regarding what constitutes correct explanations of observed facts are less important than are correct observations of fact. During the past few years there has been a difference of opinion regarding the extent to which the water-cement ratio - strength relation should be considered as absolute and all embracing. The most unsatisfactory feature has been the fact that different investigators could not agree upon the basic facts observed. Thus each new investigation that will bring forward more experimental evidence bearing on the controversy is a real contribution.

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[1] H. J. Gilkey, "Water Gain and Allied Phenomena," *Engineering News-Record*, February 10, 1928.

VOLUME CHANGE OF CONCRETE

By C. H. Scholer[1] and E. R. Dawley[2]

Synopsis

This investigation was undertaken with the intention of determining the reason for the apparent difference in the number and character of shrinkage cracks in those concrete pavements made of cement and aggregate containing very little coarse aggregate, compared with the cracks in pavements made of concrete containing the customary proportion of coarse aggregate.

This paper includes a description of the apparatus which was developed for measuring the expansion and contraction of concrete specimens, a description of the form which was especially designed to prevent external forces from acting on the specimen, and a report of the volume changes measured on several hundred specimens over a period of a little more than two years.

The investigation differs from other investigations of volume change in one important respect, that is, the measurement of the change in length of each specimen was started 30 minutes after the mixing water was added. Other investigators, using a contact method of indicating change in length, were forced to wait until after the concrete had set before starting the measurements. In some series of this investigation the only difference in volume change obtained among the different mixes occurred during the period between the first reading and the initial set.

Introduction

For many years, the engineer's conception of concrete has been undergoing a change. The old idea of a rock-like crystalline substance has been replaced by the idea that concrete is a combination of a crystalline solid and a plastic mass which expands and contracts with temperature changes like steel, which expands and contracts with moisture change like wood, and which suffers a plastic deformation under continuous load like asphalt. Provisions for these volume changes are made in all exposed concrete structures whenever possible, as, for example, expansion joints in concrete roads and sidewalks, and rollers or rockers in bridges.

This paper treats not only with the changes occurring in hardened concrete, but also with the initial expansion or contraction which occurs during the hardening period. Whether expansion or contraction will occur in a freshly placed batch of concrete mixture depends almost entirely on the treatment it receives after the water is added. If the mixture is placed in a leaky or porous form and exposed to the air on top, rapid and erratic shrinkage will occur. This shrinkage is especially rapid up to the time of initial set. After the initial set, contraction ceases and a slight expansion occurs, which continues up to about 24 hours. From 24 hours to 4 or 5 days, there is little change in length, after which time a slow, steady shrinkage begins which continues for many months.

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[2] Associate Professor of Applied Mechanics, Kansas State Agricultural College, Manhattan, Kans.

If, instead of a leaky form, a water-tight form is used, and the top of the concrete is covered to prevent rapid drying, this same concrete mixture assumes a widely different character. Instead of rapid and erratic shrinkage during the first 3 or 4 hours, there is little, if any, change. From 4 to 24 hours, a slow expansion occurs averaging only about one fifth as great as the contraction occurring during that time with the leaky form. After 24 hours, the behavior of either specimen is the same, that is, a slow contraction continuing for a year or more.

The foregoing may be considered to be a universal property of portland cement concretes, that is, slight expansion when cured wet, and considerable contraction, especially during the hardening period, when water is allowed to escape.

The investigation is divided into 6 parts, as follows:

1. The effect of using different aggregates which contained very little coarse material (called total aggregates in this paper).
2. The effect of using different aggregates containing the customary proportion of coarse material.
3. The effect of using different fine aggregates in sand-cement mortars.
4. The effect of varying the cement content or richness of mix of sand-cement mortars.
5. The effect of varying the water-cement ratio in sand-cement mortars.
6. A study of the volume change of a miscellaneous group of specimens, including the following:
    (*a*) The measurement of the warping or bending of specimens during curing.
    (*b*) The effect of wetting specimens after air-curing.
    (*c*) Volume change of neat cement.
    (*d*) Volume change of plaster of Paris.
    (*e*) Volume change of an early-strength cement.

MEASURING APPARATUS

The instrument finally developed for measuring change of length was an optical comparator consisting of two parallel microscopes mounted on a slate base (see Fig. 1). The left-hand microscope is mounted directly on the slate base, while the right-hand microscope is mounted on the carriage of an interferometer, which in turn is attached to the slate base. The position of the carriage is indicated by the dial and pointer midway between the microscopes, which counts complete revolutions of the screw. The graduated dial at the right of the interferometer is used to measure the fractions of a revolution. The interferometer screw has 40 threads per inch, and the dial is divided into 500 parts, making one division on the dial equivalent to 0.00005 in.

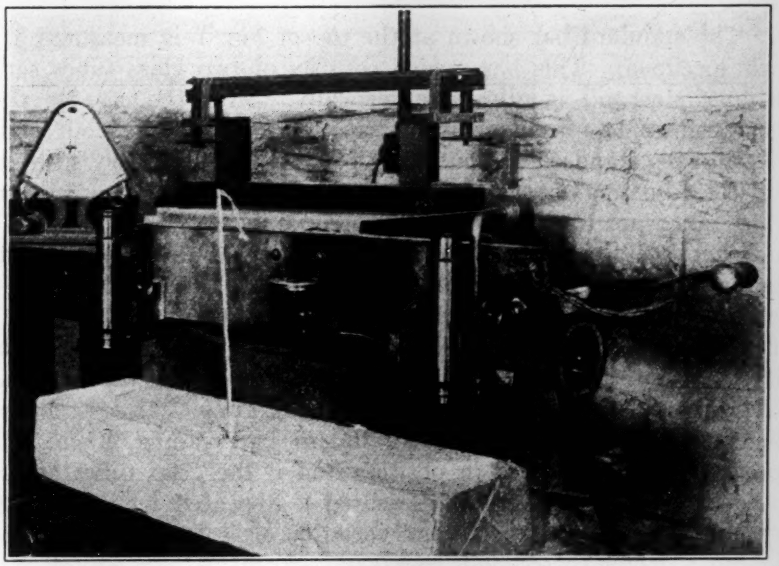

FIG. 1.—Optical Comparator with Specimen in Place.

The microscopes are fitted with cross-hairs and focusing racks. To eliminate parallax, accurate adjustment of the focus is necessary. Measurement of this showed the maximum variation in the vertical distance between the target and the bottom of the microscope for successive adjustments to be ± 0.001 in. The gage length of each specimen is 20 in. This gage length is marked by short pieces of 7-mm. glass tubing set vertically in the concrete.

The gage length of a specimen is measured as follows: The specimen is placed on the carriage and carefully located so that a line joining the axes of the microscopes coincides with a line joining the centers of the glass tubes. Next, the microscopes are focused on the glass tubes so that both tubes and cross-hairs remain motionless when the eye is moved across the eyepiece. The carriage is then moved so that the left-hand glass tube is just tangent to the cross-hair in the left-hand microscope. The right-hand microscope is now moved by the interferometer screw until its cross-hair is just tangent to the right-hand glass tube. The dial readings then indicate the gage length.

The standard bar shown at the top of Fig. 1 is measured after each specimen. This bar, which consists of two glass tubes set in an invar steel rod, is adjustable vertically. After the gage length of the specimen has been measured, the specimen is rolled out of the way and the standard bar put in its place. The bar is moved by the vertical adjusting screws on its own frame until it is in focus, care being taken not to disturb the microscopes in any way. The difference between the reading on the specimen and the reading of the standard bar gives an index of the length of the specimen.

The first reading on each specimen is taken within 30 minutes of the time the water is added to the mixture. As soon as the glass tubes are inserted, the specimen is placed on the comparator and adjusted, and the microscopes focused accurately. The specimen is then gently rolled aside and a standard bar reading taken. The specimen is again placed in position and if the glass tubes are still in focus, the gage length is measured. Repeated readings on the same specimen show a maximum variation of ± 2 dial divisions from the mean, which corresponds to 0.0005 per cent.

THE FORM

Since the character of form used in molding the specimens greatly influences the resulting volume change, the specimens were isolated from the rigid forms by inserting slabs of soft rubber, 1 in. thick, between the form and the concrete. A paper form was placed inside the rubber lining and the concrete was poured into this. An expansion of 0.02 per cent, which represents the maximum obtained, will produce a compressive stress of less than $1\frac{1}{2}$ lb. per sq. in. when acting against this rubber lining.

During the first part of the investigation, the rubber slabs were held in place by a slat-like form which allowed any free water to escape. Figure 2 shows the changes in length of 6 such identical specimens of 1:4 concrete, with a water-cement ratio of 0.7. Every effort was made here to produce exactly similar specimens; there were no particular differences in humidity or temperature. The specimens remained in the forms for 30 hours and then were cured in laboratory air. Beginning with the first reading, the curves start to diverge and continue this till the time of final set. From 4 hours to 8 days, little difference is shown, but from 8 days on there is a greater divergence than before. Data of this character were almost worthless for com-

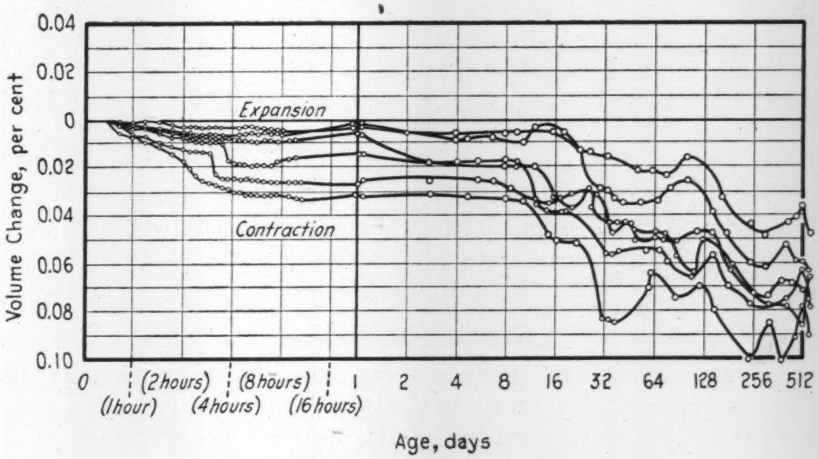

FIG. 2.—Curve Showing Effect of Leaky Forms.
Blue River Total Aggregate, Mix, 1:4, Water-Cement Ratio, 0.7.

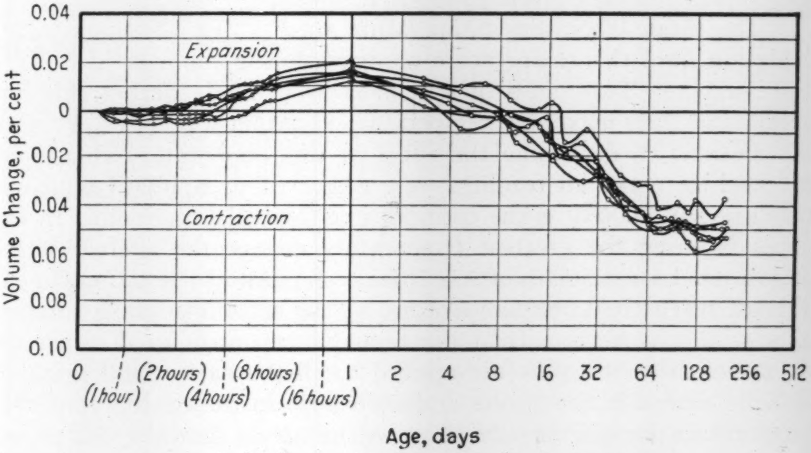

FIG. 3.—Curve Showing Effect of Water-Tight Form.
Blue River Total Aggregate, Mix, 1:4, Water-Cement Ratio, 0.7.

parative purposes. Quite a little water dripped from each of these specimens during the first few hours.

In a later series, using a drier mix, very little water escaped and the curves were grouped more closely together. This led to the adoption of a water-tight metal form. Figure 3 shows the changes in length of the same kind of concrete as Fig. 2 but molded in the water-tight form. Here (Fig. 3) instead of decided contraction up to the time of final set, there was little change until after 4 hours. From 4 to 24 hours a gradual expansion occurred (maximum of 0.02 per cent in the case of one specimen). After 1 day, a steady contraction occurred; the original length being reached in about 1 week. Although the specimens were only in the form for 30 hours in each case, the effect of the leaky form was greater at 1 year than at 4 hours.

GENERAL PROCEDURE

All specimens were made in the morning by one operator. The first reading was taken fifteen to thirty minutes after the mixing water was added. The temperature of the specimen, temperature of the air, and relative humidity of the air were recorded at each reading. The relative humidity of the air varied from 34 to 71 per cent. The air temperature varied from 65 to 91° F.

The mean laboratory temperature was 71° F. The maximum deviation from this temperature occurred during the months of July and August. Two series of specimens were made during this hot period and their maximum temperature variation was + 19° F. from the mean. To determine the effect of this temperature change on the average curve all readings were corrected to standard temperature using 0.0000055 as the coefficient of thermal expansion. In the series suffering the greatest temperature change the average curve was lowered a maximum of 0.007 per cent. All of the six specimens did not reach the same temperature at the same age which resulted in a smaller correction than the temperature range would indicate. A correction for temperature applied to all the data would result in a slight change in the curves and no change in the conclusions. No temperature corrections were made on the curves shown in this paper.

Forms were removed after 30 hours, and for the next 6 days the specimens were kept on an oiled board 2 in. thick. After 1 week all specimens were stored in racks having wooden shelves.

MATERIALS

Coarse Aggregate:

The coarse aggregate used was a crushed sandstone from Lincoln County, Kans. This stone was crushed so that 100 per cent passed the 1½-in. sieve, 65 per cent was retained on the ¾-in. sieve, while 100 per cent was retained on the No. 4 sieve. The French coefficient was 11; and the weight was 88 lb. per cu. ft.

Total Aggregate:

Three different kinds of total aggregates were used, all of which passed a ¾-in. sieve:

1. Crushed flint from Joplin, Mo., weighing 111 lb. per cu. ft. and having a fineness modulus of 4.5.

2. Blue River total aggregate, a clean, siliceous aggregate pumped from the Blue River near Manhattan, Kans., weighing 113 lb. per cu ft. and having a fineness modulus of 4.1.

3. Blue Rapids total aggregate, a clean, siliceous aggregate obtained from a dry pit near Blue Rapids, Kans., weighing 117 lb. per cu. ft. and having a fineness modulus of 4.0.

Fine Aggregate:

Fine aggregates from three sources were used. One hundred per cent of all fine aggregates passed a ⅜-in. sieve.

1. *Kansas River Sand.*—This sand was pumped from the Kansas River at Manhattan, Kans., and was a typical river sand of good quality, weighing 107 lb. per cu. ft. and having a fineness modulus of 3.0.

2. *Crushed Flint Sand.*—This material, which consisted of flint tailings from the zinc mines near Joplin, Mo., was crushed until it approximated the gradation of ordinary sand. The fineness modulus was 2.8, and the weight was 93 lb. per cu. ft.

3. *Standard Ottawa Sand.*

Cement:

One brand of portland cement was used throughout the investigation. The physical properties were as follows: Normal consistency, 24 per cent; initial set, 4 hours 50 minutes; final set, 6 hours 15 minutes; fineness, 86.9 per cent passing No. 200 sieve; 7-day strength, 1:3 standard mortar, tensile, 343 lb. per sq. in, compressive, 2390 lb. per sq. in.; 28-day strength, tensile 433 lb. per sq. in., compressive, 3033 lb. per sq. in.

RESULTS

Effect of Total Aggregate versus Coarse Aggregate:

One of the reasons for undertaking this investigation was to determine, if possible, the reason for the apparent difference in the number and character of shrinkage cracks in concrete pavements made with aggregate containing very little coarse material (called total aggregate here) and the cracks in pavements containing the customary proportion of coarse aggregate.

Total Aggregate.—Figure 4 shows the volume change of concrete made with three different total aggregates containing very little coarse material. Each plotted point represents the average of six specimens made in the water-tight form. The mix was 1:4 by volume and the water-cement ratio was 0.7. The aggregates from Blue River and Blue Rapids show very close agreement, while the Joplin flint shows somewhat less volume change. This is interesting in view of

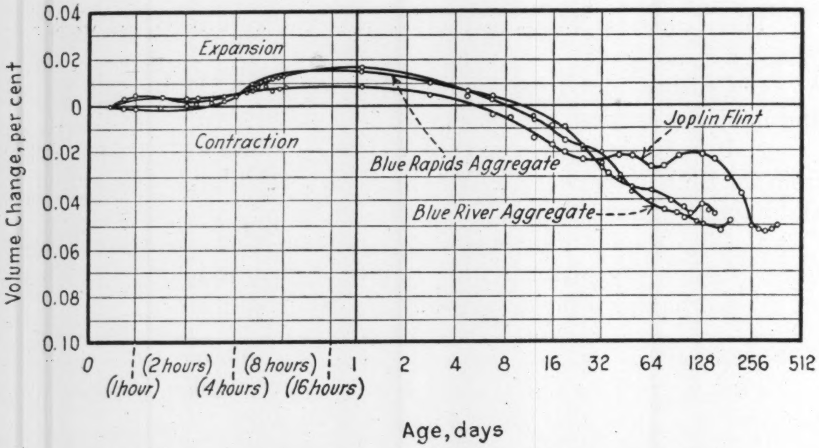

FIG. 4.—Curve Showing Effect of Different Total Aggregates.
Mix, 1:4, Water-Cement Ratio, 0.7.

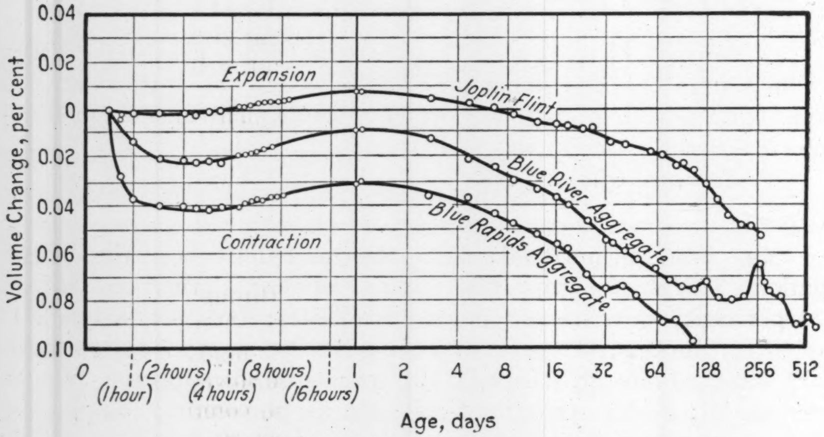

FIG. 5.—Curve Showing Effect of Different Total Aggregate.
Mix, 1:4, Water-Cement Ratio, 1.0.

the fact that more blow-ups have occured in pavements where crushed flint aggregate was used.

Figure 5 shows the same three total aggregates, and the same mixes as Fig. 4, but with a water-cement ratio of 1.0 instead of 0.7. The curves of Fig. 5 are quite different; the Blue River and Blue Rapids aggregates showing considerable initial contraction, and showing a faster rate of shrinkage after 24 hours, while the Joplin flint shows even greater volume constancy than before. The mixtures shown in Fig. 4 were all characterized as dry but workable, while in Fig. 5 the Blue River aggregate was noted as wet, while the Blue Rapids aggregate was called very wet.

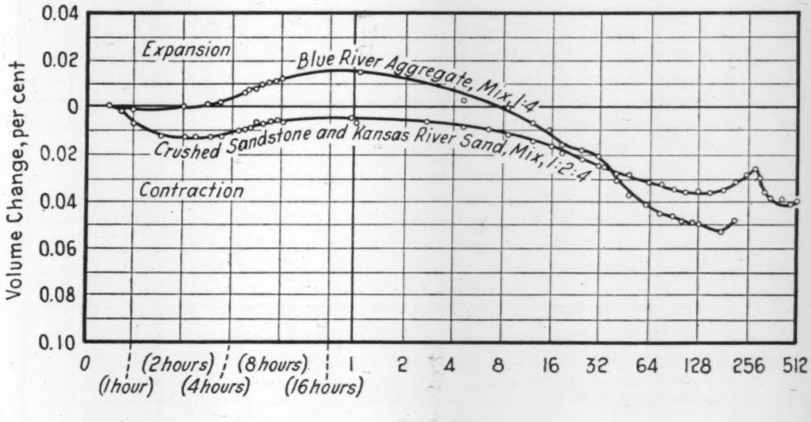

FIG 6.—Curve Showing Effect of Coarse Aggregate.
Water-Cement Ratio, 0.7.

Coarse Aggregate.—One series of tests on specimens containing crushed sandstone are available here. The fine aggregate was Kansas River sand. Figure 6 shows the curve for this series in which the mix was 1:2:4 by volume, and the water-cement ratio was 0.7. For comparison, the Blue River total aggregate curve shown on Fig. 4 (mix 1:4) is reproduced again in Fig. 6. As before, each plotted point represents the average of 6 specimens. The 1:2:4 mix containing the coarse aggregate appears to have less volume change than the total aggregate concrete but the difference between the curves is hardly sufficient to account for the difference in the appearance of pavements made from the two mixes. These two mixes were poured in a covered water-tight form which retained all the water for 30 hours after pouring. Such conditions are almost never obtained in pavement construction.

Attention is called to the hump appearing in the curve in Fig. 6 for the 1:2:4 mixture at about 256 days. An inspection of Figs. 7 and 8 shows that this is not an uncommon characteristic. Each plotted point represents the average of 6 specimens. A study of the temperature and humidity over this period which is usually over 100 days, fails to disclose any reason for this hump.

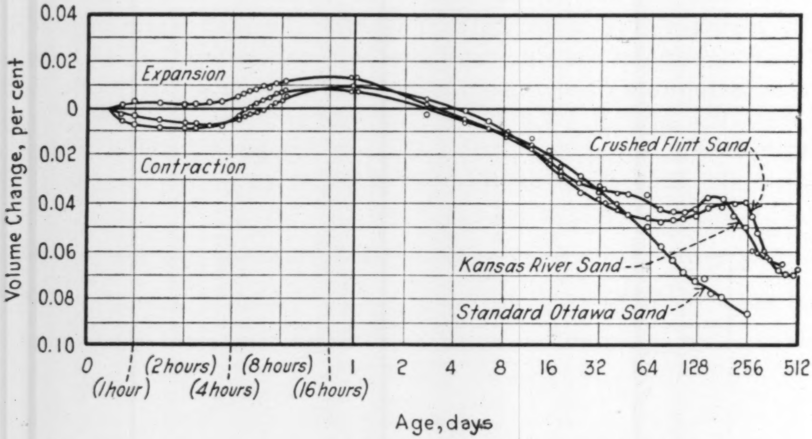

FIG. 7.—Curve Showing Effect of Different Fine Aggregates on the Volume Change of Concrete.

Mix, 1:3, Water-Cement Ratio, 0.7.

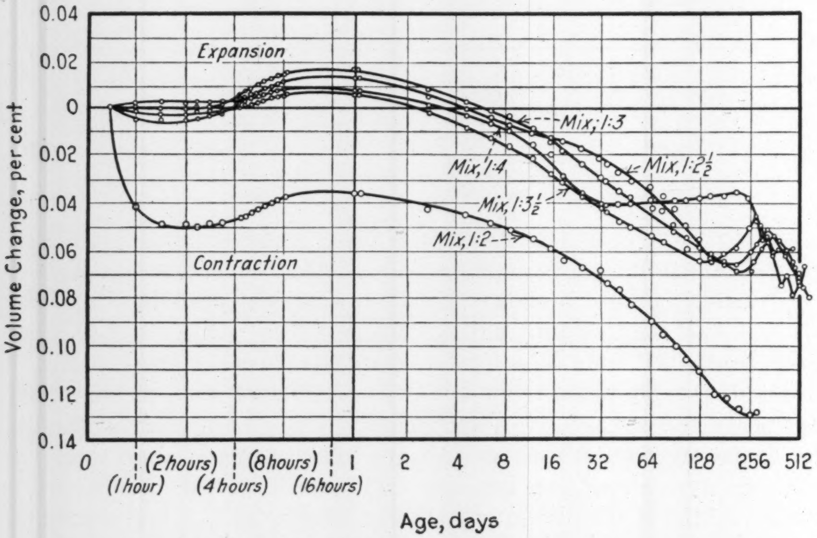

FIG. 8.—Curve Showing Effect of Richness of Mix Using Kansas River Sand.

Water-Cement Ratio, 0.6.

Effect of Different Fine Aggregates:

The effect of the fine aggregate on the volume change of concrete was investigated using mortar specimens mixed in the proportion of 1:3 by volume with a water-cement ratio of 0.7, and using sands from three different sources: Standard Ottawa sand, Kansas River sand, and crushed flint sand. Figure 7 shows the curves for these three sands. There is little difference in the volume change of these three materials. The consistency for these tests was workable but not wet.

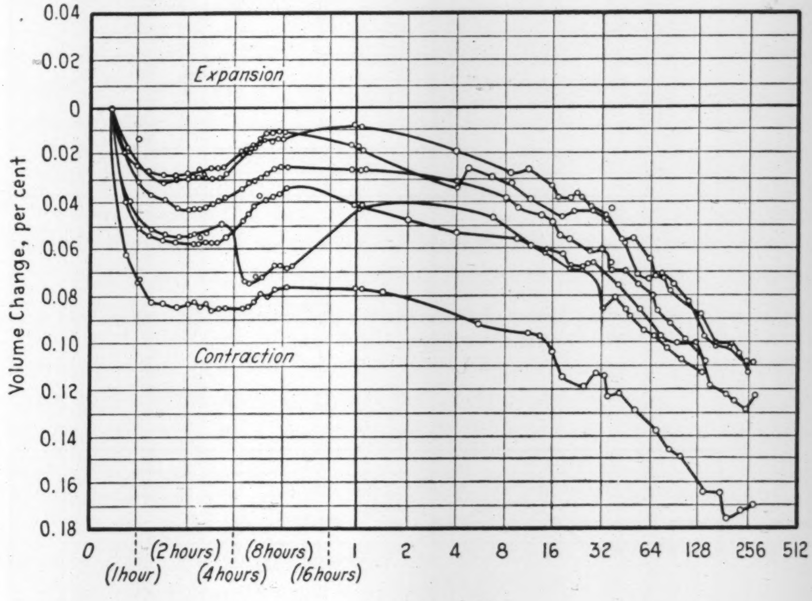

FIG. 9.—Individual Curves for Six Specimens, Kansas River Sand Mortar. Mix, 1:2, Water-Cement Ratio, 0.6.

Effect of Richness of Mix:

The effect of richness of mix on volume change was investigated by measurements on five different mortar mixes using Kansas River sand, and a water-cement ratio of 0.6. The mixes were 1:2, 1:2½, 1:3, 1:3½, and 1:4 by volume.

Figure 8 shows the result of this series of tests. Since the water-cement ratio was maintained constant, the consistency varied with the mix. The 1:2 mix was characterized as very sloppy; the

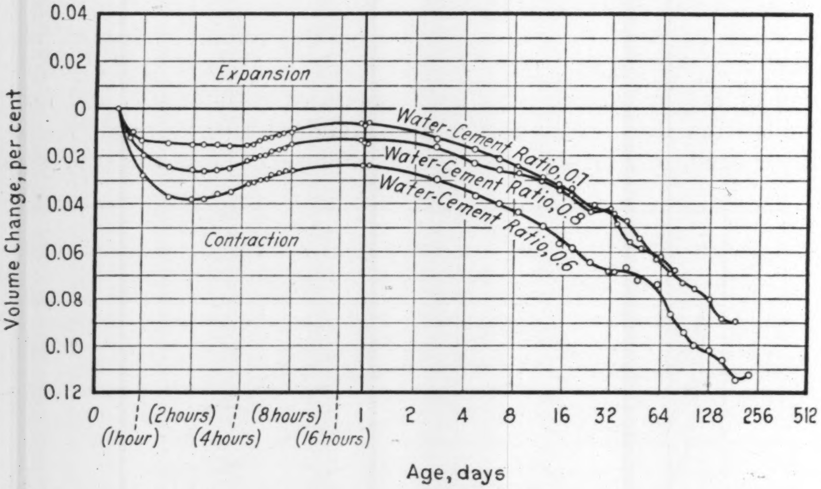

FIG. 10.—Curve Showing Effect of Different Water-Cement Ratios on Kansas River Sand Mortars, 1-in. Slump.

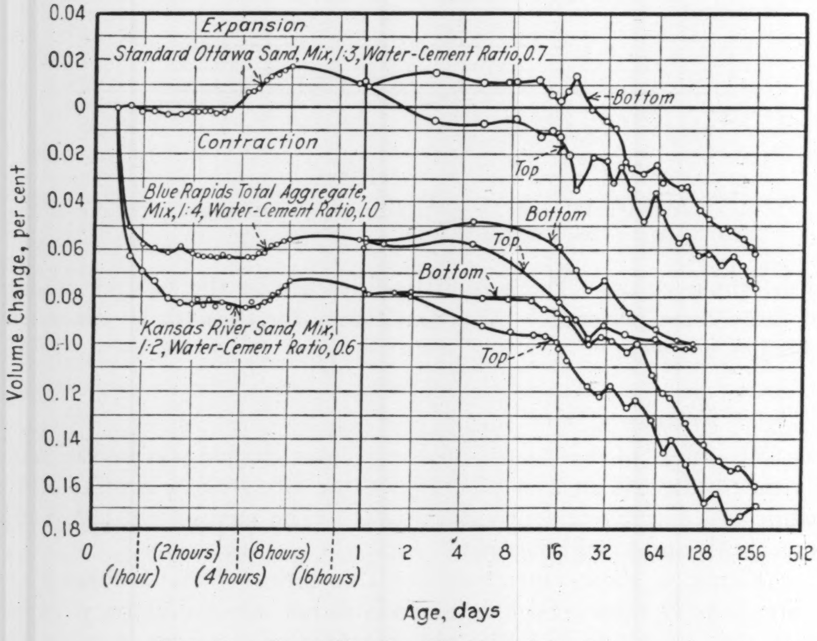

FIG. 11.—Curve Showing Warping of Specimens.

1:2½ mix as dry but workable; while all leaner than 1:3 were called very dry. The curve for the 1:2 mix shows a character decidedly different from the drier mixes. Here again, each plotted point represents the average of 6 specimens. The shrinkage during the first 15 minutes is very noticeable in the 1:2 mix. In order to show the variation among the individual specimens in this series (mix 1:2, water-cement ratio 0.6) Fig. 9 has been prepared. The difference between the curves here is not readily explained, since the 6 specimens are all identical as far as mix, water-cement ratio, consistency, manipulation, forms, and curing are concerned. The average curve for the 1:2 mix, which is shown in Fig. 8, is much less significant than the average curve from a series such as the one shown in Fig. 3. The grouping of the curves of Fig. 3 may be taken as typical of most of the data reported in this paper, the only exceptions being in the cases of extremely wet mixes.

For dry mixes, apparently the richness of mix has little influence on the rate of volume change.

It will be noted in Fig. 8 that most of the change in the 1:2 mix occurred in the first few hours. If these curves were placed together at an age approximating the point of final set, say at 8 hours, the difference in volume change is not at all marked. Figure 12 shows the curves of this series moved vertically to give the zero reading at an age of 8 hours.

Effect of Different Water-Cement Ratios:

The effect on volume change of different water-cement ratios was studied for Kansas River sand mortars mixed with cement paste in sufficient quantity to produce a 1-in. slump. The cement pastes used were mixed with water in the following ratios: 0.6, 0.7, and 0.8. These mixtures were all characterized as jelly-like and workable.

The proportions of mix which gave these water-cement ratios were as follows:

WATER-CEMENT RATIO	MIX, BY VOLUME
0.6	1:2.2
0.7	1:2.9
0.8	1:3.4

Figure 10 shows the average curves for these three groups. All show initial contraction with the curve for a water-cement ratio of 0.6 which was perhaps the best lubricated mixture showing the greatest shrinkage. With the exception of the first 60-minute period, there was little difference in the volume change of these three mixes.

MISCELLANEOUS TESTS

Warping of Specimens.—All specimens in this investigation were poured in a water-tight rubber-lined form which remained in place for 30 hours. After removal from the form, each specimen was placed on an oiled board 2-in. thick and having the same length and width as the specimen. The specimen after remaining on this board for one week, was then stored on a specimen rack having wooden shelves. The possibility of bending or warping was recognized and this tendency was measured in several specimens. These specimens were molded in the usual way, except that before molding, two corks were attached to the bottom of the form 20 in. apart. After 24 hours, the specimens were removed from the molds, the corks removed, and glass rods inserted in the holes and cemented in place with plaster-of-Paris. Readings were then taken on both sets of rods by turning the specimen over. The specimens were always stored right side up, and only inverted for the few minutes required for the reading.

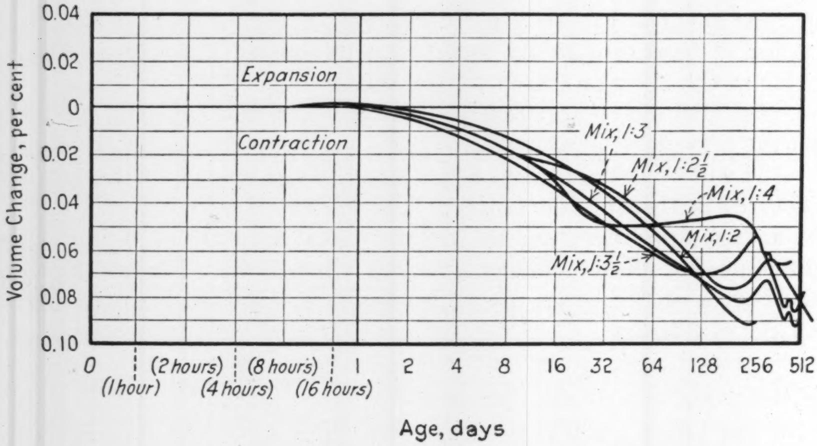

FIG. 12.—Curve Showing Effect of Richness of Mix After 8 Hours. Water-Cement Ratio, 0.6.

Figure 11 shows the results obtained on three of these individual specimens. Some bending is indicated which shows a tendency to become smaller with age.

The bottom in all cases contracted less than the top, probably because the presence of the boards against the bottom prevented the escape of moisture to some extent, while the top surface (after 30 hours in the forms) was exposed to the air, allowing free evaporation.

Neat Cement.—A neat cement specimen was made with a water-cement ratio of 0.6 which made a very sloppy mix. Four hours elapsed before the specimen was rigid enough to hold the glass rods in place, which prevented quantitative comparison of total volume change. The temperature of this specimen increased to a maximum of 86° F. at 9 hours, the room temperature being 70° F. Measurements taken after 4 hours showed rapid expansion which reached a maximum of 0.05 per cent at an age of 24 hours. Following this, a slow contraction occurred, leaving a net expansion of 0.01 per cent at 1 month.

Plaster-of-Paris.—A specimen of plaster-of-Paris was made using sufficient water to produce the same consistency as the neat cement specimen, that is, very sloppy. The temperature of this specimen increased rapidly and reached a maximum of 126° F. after 40 minutes, the room temperature being 65° F. This specimen exhibited sudden and extreme expansion, showing an increase in length of 0.27 per cent in 1½ hours. Following this, the specimen gradually contracted until at 2 months, the net expansion was 0.07 per cent.

Effect of Wetting Air-Cured Specimens.—The effect of wetting was measured on 8 specimens of varying richness of mix. All specimens were made from Kansas River sand mortar with a water-cement ratio of 0.6. These specimens were air-cured for more than 200 days. Four specimens were placed in saturated air, while four were soaked in a tank of water. All specimens showed steady expansion; the water-soaked specimens expanding more rapidly at first than those in moist air. However, after 1 month, the specimens in moist air had elongated practically as much as those soaked in water. The rich mixes showed the greatest expansion, due to wetting (0.05 per cent in 1 month for the 1:2 mix) while the lean mix showed the least increase in length, (0.02 per cent in 1 month). These results are in conformity with the results of other investigations of this kind.

Early-Strength Cement.—One specimen of Kansas River sand with an early-strength cement in the proportion of 1:3 by volume and a water-cement ratio of 0.7 was compared with a specimen of the same mix and water-cement ratio using portland cement. At 2 hours, the early-strength cement specimen had contracted 0.028 per cent, while the portland cement had contracted 0.009 per cent. From 2 hours to 1 day, the expansion for portland cement concrete was 0.020 per cent, and for early-strength cement concrete 0.025 per cent. The contraction from 24 hours to 96 days for portland cement concrete was 0.050 per cent, and for early-strength cement concrete 0.076 per cent. Ordinary portland cement concrete of 1:3 mix with a water-cement ratio of 0.7 showed less volume change than the early-strength cement concrete at all ages.

CONCLUSIONS

Expansion with wetting and contraction with drying appears to be a universal property of portland cement concrete.

The variables here studied included the effect on volume change of forms, coarse aggregate, fine aggregate, richness of mix and water-cement ratio. Of these variables, the forms appeared to exert the greatest influence on the character of the volume change.

Leaky forms which allowed free water to escape caused contraction for the first four or five hours, and permanently altered the character of the mixture. The contraction was very erratic. Similar specimens gave different results, especially during the hardening period.

Similar specimens molded in water-tight forms showed more consistent volume change. When the specimens were mixed rather dry, little volume change occurred for the first few hours; the tendency being toward a slight expansion which increased up to 24 hours. The probable limit of this expansion for ordinary mixes is about 0.02 per cent. When the specimens were mixed rather wet, initial contraction occurred, the amount of which depended upon the richness of the mix and the character of the aggregate.

There was little difference in the character of volume change between mixtures using crushed sandstone for coarse aggregate, and mixtures using total aggregate having few large particles when water-tight forms are used. These tests indicated the mix having the crushed sandstone to be a little more constant in volume.

The character of the fine aggregate exerted practically no influence on the volume change, crushed flint sand, standard Ottawa sand, and Kansas River sand, showing practically the same volume change.

The richness of mix, in the case of dry mixes, had little influence on the volume change, although the leaner mixes showed somewhat less change than the rich mixes.

Mortar mixes of constant consistency (1-in. slump) and variable water-cement ratio showed the greatest shrinkage for the lowest water-cement ratio (which was also the richest mix). Water-cement ratios of 0.7 and 0.8 showed less shrinkage.

The mixtures studied and reported here are for the most part more nearly like pavement concrete than like the concrete used in reinforced building construction. It appears probable that the latter material would show greater contraction than the former.

SOME RESULTS OF FREEZING-AND-THAWING TESTS MADE WITH CLAY FACE BRICK

By L. A. Palmer[1] and J. V. Hall[1]

Synopsis

Four different types of face brick were studied for the purpose of determining a possible relationship between resistance to freezing and thawing of saturated brick and their percentages of absorption. Two representative lots of each type of brick were selected. Percentage of absorption, as determined both by immersion in water at room temperature and by immersion in boiling water, flexural strengths and compressive strengths were determined for each lot of brick, in the first lot as received and in the second after 100 cycles of alternate freezing and thawing.

Specimens in the higher range of absorption for each type of brick were weakened relatively more in compressive strength than were specimens of the same type but of the lower range of absorption. This is determined by averages of the two groups, but there were many exceptions among the individual specimens for each type of brick. The average decrease in flexural strength of bricks of the higher range of absorption was not noticeably different from that of bricks of lower absorption, for each of the four types.

The individual specimens subjected to freezing and thawing were increased in percentage of absorption, as determined both by immersion in water for at least 48 hours at normal room temperature and by immersion in boiling water for a period of 5 hours. The pore ratio (Schurecht ratio) was altered in practically every case, the number of instances wherein it was increased being about equal to that wherein it was decreased.

The data do not present evidence in conflict with the general belief that there is no definite relationship between the absorption and the weather resistance of clay brick, when various types of products are considered.

Introduction

One of the by-products of an investigation entitled "Damp-Wall Interiors," sponsored by the American Face Brick Association, has been the acquisition of a limited amount of data pertaining to the resistance of face brick to the alternate freezing and thawing of moisture saturating them.

The various members of the Society's Committee C-3 on Brick have maintained that the relation, if any exists, between the absorption of a brick made from clay or shale and its weather resistance is much too indefinite to warrant the use of that property as a basis for specifications. There have been in the past both careful field studies and laboratory measurements indicating that such is the case. The general belief of Committee C-3 has been somewhat as follows: Were all brick made from one clay (homogeneous throughout) and molded by the same process, such a distinct relationship would no doubt be found to exist. Actually, however, many variable conditions tend to obscure this relationship and the number of exceptions in any case is such that an absorption requirement as a standard is not practicable.

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[1] Research Associate of the American Face Brick Association at the U. S. Bureau of Standards, Washington, D. C.

There is nothing herein presented that is not in agreement with this general belief. McBurney[1] has already shown that the molding process is a factor that must be considered. This writer has also very clearly discussed the work of Kreüger.[2] Schurecht[3] has shown that permeability of surface as well as what he has defined as the "pore ratio" must be taken into account when resistance to frost action is considered. There are probably other factors, the existence of which is not realized until the study is extended and broadened. At least one such factor will be mentioned in this paper.

The purpose of this paper is essentially to present data. The range of materials studied was of necessity limited. The interpretation of these data as here presented may be only partially correct and it is therefore desirable that the various readers themselves endeavor to analyze them.

MATERIALS AND TEST METHODS

Four types of brick were studied in this investigation. Types Nos. 1 and 2 were smooth, dry-press brick, type No. 1 being made from surface clay and No. 2 from shale. Types Nos. 3 and 4 were stiff-mud, side-cut shale brick. Each type is a product of a different manufacturer. The brick represented more or less a "vertical cross-section" from the kiln. Certain samples of brick of type No. 2, however, were believed by the manufacturer to be under-burned and were selected from material not marketed. The softest and hardest burned brick (as produced in the manufacturer's kiln) as well as those of intermediate hardness were included among each of the four types tested.

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[1] J. W. McBurney, "The Water Absorption and Penetrability of Brick," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 711 (1929).

[2] H. Kreüger, "Utredning rörande klimatisk inverkan På byggnadsfasader," *Ingeniors Ventenspake Akademein No. 24*, p. 1023.

[3] Senior Fellow, National Terra Cotta Soc. Research Fellowship at the U. S. Bureau of Standards, Washington, D. C. Unpublished data.

The laboratory procedure in brief was as follows: A representative number of brick "as received" was tested for flexural and compressive strengths, and for absorption both by immersion in water at normal room temperature for at least 48 hours and by immersion in boiling water for 5 hours. These bricks are designated Group I for each of the four types and were not subjected to freezing and thawing.

A similar representative number of bricks of each type, designated Group II, were subjected to freezing and thawing. Having determined the absorption by cold immersion and by boiling, the bricks were dried to constant weight, again immersed in water at normal room temperature for a period of 48 hours, and transferred immediately while thus saturated to a freezing chamber. While freezing, the bricks were partially immersed in water so that drying out was impossible. The temperature of the freezing room ranged usually from 12 to 22° F. The time of freezing was about 18 hours. The bricks were then thawed by immersion in water at a temperature of 60 to 70° F. for approximately 6 hours. By admitting steam and by agitating the water in the tank, the initial cooling of the water which would be produced when the cold specimens were introduced into the tank was prevented. All bricks of Group II were subjected to 100 freezing-and-thawing cycles.

Following the 100 cycles of freezing and thawing, the bricks were weighed, placed in an oven (temperature 110 to 140° F.) and dried to constant weight. This final dry weight, after 100 cycles, was compared with the original dry weight determined prior to freezing and thawing, and any loss in weight was noted. After drying, absorption both by cold immersion and boiling was redetermined and the values for each brick, after the 100 cycles, were compared with those determined prior to freezing and thawing. The bricks were then again dried to constant weight and their flexural and compressive strengths determined.

Flexure and compression tests were made in accordance with A.S.T.M. methods.

DATA AND DISCUSSION

The results of the tests are given in Tables I and II, Table I containing the Group I tests and Table II the Group II tests for each of the four types of brick. The individual results are arranged in order of decreasing percentage of absorption by boiling.

TABLE I.—TESTS OF GROUP I BRICKS OF FOUR TYPES.

Bricks Not Subjected to Freezing and Thawing.

Specimen	Absorption by 5 Hours Boiling, per cent of dry weight	Ratio, Cold Absorption Divided by Boil Absorption	Modulus of Rupture, lb. per sq. in.	Compressive Strength (flat), lb. per sq. in.
TYPE NO. 1				
No. 177	14.6	0.848	226	4 257
No. 159	14.2	0.839	549	3 373
No. 160	13.8	0.841	302	4 200
No. 167	13.8	0 839	352	4 030
No. 267	13.7	0.832	300	4 247
No. 265	13.6	0.834	415	4 335
No. 204	13.2	0.814	744	4 240
No. 279	13.1	0.837	450	4 070
No 227	13.1	0.820	478	4 360
No. 106	13.0	0.812	657	6 520
No. 264	12.5	0.792	552	4 825
No. 243	12.8	0.812	788	6 125
No. 241	12 3	0.806	670	5 675
No. 232	12.2	0.793	219	6 060
No. 1	12.2	0.816	743	5 920
No. 152	12.2	0.810	885	6 775
No. 443	12.2	0.807	590	7 200
No. 434	12.0	0.808	600	5 700
No. 441	12.0	0.808	770	7 875
No. 433	11.9	0.769	826	9 400
No. 162	12.0	0.802	735	7 350
No. 182	11.7	0.793	720	6 135
No. 261	11.7	0.790	782	7 385
No. 84	11.6	0.791	324	7 800
No. 39	11.6	0.803	696	6 160
No. 439	11.3	0.804	690	7 400
No. 444	11.3	0.797	1 075	7 875
No. 75	11.4	0.791	822	7 275
No. 282	11.3	0.788	470	7 000
No. 255	11.3	0.769	824	4 340
No. 10	11.2	0.804	619	6 002
No. 270	11.2	0.785	682	5 260
No. 254	11.2	0.784	850	7 775
No. 172	11.1	0.801	864	4 665
No. 28	11.0	0.789	326	6 180
No. 437	11.0	0.758	637	6 615
No. 440	10.9	0.800	614	1 590
No 438	10.9	0.763	975	8 270
No 436	11.0	0.760	839	6 940
No. 24	10.8	0.803	657	6 995
No 435	10.8	0.801	504	7 400
No. 262	10.2	0.745	606	9 100
TYPE NO. 2				
No. 337	16.1	0.845	665	2 350
No. 357	16.0	0.850	636	3 370
No. 346	16.1	0.848	667	3 140
No 351	16.1	0.858	626	3 310
No. 360	16.1	0.850	487	2 910
No. 335	16.1	0.848	600	3 530
No. 314	16.2	0 850	843	3 100
No. 264	16.0	0 850	724	3 680
No. 309	15.9	0.846	805	3 460
No. 174	15.9	0.846	700	3 170
No. 256	16.1	0 850	710	3 770
No. 325	16.2	0 836	417	3 160
No. 330	15.8	0.836	717	3 125
No. 334	15.7	0.830	428	3 220
No. 327	15.8	0.831	686	3 715
No. 230	15.7	0.850	800	3 040
TYPE NO. 2—(*Continued*)				
No. 296	15.7	0.836	804	4 100
No. 347	16.0	0.850	696	3 680
No. 348	15.8	0.831	785	3 450
No. 349	15.9	0.850	735	3 230
No. 352	15.8	0.820	765	3 940
No. 359	15.9	0.843	668	3 505
No. 356	15.7	0.853	574	3 300
No. 333	15.7	0.836	730	4 000
No. 329	15.7	0.825	550	3 450
No. 354	15.6	0.826	811	3 900
No. 328	15.7	0.825	550	3 450
No. 332	15.0	0.838	735	3 590
No. 326	15.6	0.832	705	3 400
No. 331	14.7	0.807	1 010	4 270
No. 338	14.2	0.813	961	4 350
No. 344	14 0	0.803	730	4 315
No. 358	13.5	0.810	1 030	4 485
No. 340	13.7	0.803	930	4 225
No. 343	13.6	0.803	735	4 040
No. 310	13.4	0.800	1 240	3 630
No. 322	13.7	0.798	1 265	4 645
No. 79	13.4	0.819	808	4 300
No. 353	13.5	0.796	1 040	4 410
No. 323	13.3	0.796	1 075	5 075
No. 278	13.2	0.795	1 045	3 925
No. 342	12.9	0.801	1 160	5 430
No. 345	13.1	0.805	1 065	3 955
No. 336	12.9	0.806	1 085	5 230
No 339	12.4	0.792	1 110	5 450
No. 341	12.4	0.796	1 210	3 900
No. 350	12.4	0.798	1 025	3 980
No. 61	11.9	0.773	1 215	5 225
No. 2	11.5	0.752	895	5 350
TYPE NO. 3				
No. 424	7.5	0.728	2 060	14 080
No. 296	7.5	0.720	2 130	11 620
No. 425	7.5	0.725	2 050	13 850
No. 407	7.4	0.663	2 065	13 985
No. 412	7.4	0.665	1 990	14 195
No. 442	7.4	0.680	2 135	13 930
No. 445	7.5	0.700	2 190	13 560
No. 409	7.4	0.690	1 925	14 335
No. 68	7.3	0.677	2 100	14 290
No. 415	7.3	0.663	1 730	13 950
No. 422	7.3	0.703	1 655	13 035
No. 420	7.2	0.689	1 580	15 250
No. 444	7.2	0.651	2 020	14 580
No. 432	7.1	0.659	1 995	17 275
No. 443	7.1	0.704	2 130	14 160
No. 418	7.1	0.715	2 050	15 755
No. 57	7.0	0.632	2 420	17 065
No. 437	7.0	0.687	2 190	16 880
No. 440	7.0	0.658	2 460	14 090
No. 417	7.0	0.685	1 850	17 545
No. 406	6.9	0.675	2 220	14 095
No. 408	6.9	0.643	2 020	13 000
No. 435	6.9	0.696	1 970	15 300
No. 416	6.9	0.684	2 100	13 810

TABLE I. TESTS OF GROUP I BRICKS OF FOUR TYPES (*Continued*)

Bricks Not Subjected to Freezing and Thawing.

Specimen	Absorption by 5 Hours Boiling, per cent of dry weight	Ratio, Cold Absorption Divided by Boil Absorption	Modulus of Rupture, lb. per sq. in.	Compressive Strength (flat), lb. per sq. in.
TYPE No. 3—(*Continued*)				
No. 446	6.9	0.701	2 335	16 700
No. 29	6.9	0.665	2 255	11 905
No. 4	6.8	0.658	2 180	14 310
No. 447	6.7	0 650	2 325	15 515
No. 434	6.7	0.655	1 725	10 995
No. 34	7.0	0.664	2 170	12 880
No. 424	6.7	0.671	1 950	15 445
No. 436	6.6	0.665	1 955	13 485
No. 410	6.5	0.653	1 740	17 620
No. 405	6.4	0.610	2 450	16 400
No. 426	6.4	0.610	2 230	13 735
No. 429	6.5	0.655	2 340	16 235
No. 411	6.3	0.609	1 775	12 435
No. 428	6.4	0.640	1 930	12 360
No. 414	6.2	0.639	2 120	15 920
No. 413	6.2	0.626	2 095	15 070
No. 427	6.0	0.582	1 865	15 825
No. 421	6.0	0.634	2 325	14 600
No. 404	5.6	0.603	2 330	15 220
No. 438	5.5	0.635	2 040	18 445
No. 419	5.7	0.620	2 460	13 570
No. 433	5.3	0.610	2 400	11 985
No. 431	4.5	0.438	2 310	15 355
TYPE No. 4				
No. 458	9.9	0.619	745*	6 842
No. 474	9.2	0.600	1 790	15 810
No. 471	9.0	0.613	730	11 150
No. 445	8.7	0.569	1 185	14 500
No. 448	8.4	0.600	1 590	11 450
No. 460	8.4	0.595	1 780	12 800
No. 481	8.4	0.592	672*	11 400
No. 455	8.3	0.590	986	14 900
No. 459	8.3	0.585	1 560	13 870
TYPE No. 4—(*Continued*)				
No. 468	8.3	0.585	688*	10 865
No. 465	8.1	0.574	1 025*	9 230
No 461	8.1	0 570	965*	12 335
No. 476	8.1	0.573	910*	13 350
No. 449	8.1	0.569	1 190	11 250
No. 470	8.0	0.571	1 740	14 700
No. 469	8.0	0.562	1 280*	15 060
No. 452	8.0	0 557	1 775	12 060
No 472	7.9	0 561	860*	11 305
No. 456	7.8	0.576	1 080	13 500
No. 450	7.8	0.563	1 250	18 535
No. 475	7.8	0.558	815*	14 100
No. 453	7.7	0.559	1 220	15 805
No. 466	7.7	0.557	1 120	14 455
No 457	7.6	0.544	960	10 450
No. 477	7.6	0.558	1 015*	14 100
No. 479	7.5	0.547	1 110	16 400
No 454	7.4	0.558	289*	14 100
No. 464	7.4	0.548	1 670	14 900
No. 451	7.1	0.541	1 300	11 150
No. 34	7.1	0.538	1 640	12 300
No. 50	7.1	0.538	1 680	16 000
No. 462	7.0	0.542	1 960	12 000
No. 463	7.0	0.543	1 830	13 315
No. 480	6.9	0.538	635*	11 416
No. 478	6.9	0.534	1 790	15 810
No. 117	6.6	0.526	977	15 980
No. 445	6.5	0.531	626*	10 900
No. 118	6.4	0.534	1 630	14 300
No. 447	6.2	0.510	1 600	16 560
No. 107	6.2	0.500	1 660	9 750
No. 120	6.1	0.494	1 595	14 600
No. 446	6.0	0.498	927	13 785
No. 38	6.0	0.496	1 045	10 700
No. 116	4.1	0.397	2 380	16 560

Specimens marked with an asterisk (*) were cracked prior to testing.

Flexural and Compressive Strengths:

If individual bricks of Group I are compared to those individual bricks of Group II having the same absorption, then any relation between absorption and weather resistance should be noticeable if such exists. Such a relationship should be most apparent among individual brick (varying in degree of absorption) made by one manufacturer by the same process and from the same clay or shale. The data of Tables I and II may therefore be averaged, condensed and rearranged. These averages are presented in Table III. The subgroups designated as I-a, II-a, etc., represent those bricks of Group I and II in the higher range of absorption. Similarly, subgroups I-b and II-b represent bricks in the lower range of absorption.

TABLE II.—TESTS OF GROUP II BRICKS OF FOUR TYPES.

All Bricks Subjected to 100 Freezing-and-Thawing Cycles

Specimen	Change in Weight, per cent of original Dry Weight	Absorption by Boiling Prior to Freezing-and-Thawing Tests, per cent of Initial Dry Weight	Absorption by Boiling After-Freezing and-Thawing Tests, per cent of Final Dry Weight	Ratio, Cold Absorption Divided by Boil Absorption Prior to Freezing-and-Thawing Tests	Ratio, Cold Absorption Divided by Boil Absorption After Freezing-and-Thawing Tests	Modulus of Rupture After 100 Freezing-and-Thawing Tests, lb. per sq. in.	Compressive Strength (flat) After 100 Freezing-and-Thawing Tests, lb. per sq. in.
Type No. 1.							
No. 214	−0.07	15.5	17.0	0.845	0.790	324	3 785
No. 253	+0.1	15.3	15.5	0.856	0.843	86	3 310
No. 245	no change	15.1	15.3	0.849	0.844	382	5 550
No. 31	no change	15.1	15.2	0.863	0.853	300	2 980
No. 208	−0.09	15.1	14.9	0.850	0.894	334	2 760
No. 279	no change	15.0	15.1	0.852	0.841	780	7 210
No. 209	+0.2	14.5	14.4	0.834	0.846	364	4 860
No. 50	−0.1	14.4	14.4	0.835	0.835	341	3 180
No. 38	no change	14.3	14.1	0.850	0.839	314	3 870
No. 19	gain of 6 g.	14.2	13.9	0.847	0.870	232	3 970
No. 47	−0.1	13.9	13.7	0.838	0.862	72	4 920
No. 193	−0.1	13.8	14.1	0.839	0.849	356	3 605
No. 203	no change	13.6	13.5	0.840	0.888	444	4 670
No. 252	−0.12	13.6	14.3	0.833	0.836	910	4 655
No. 196	no change	13.4	13.7	0.833	0.818	86	3 685
No. 251	+0.1	13.4	13.4	0.834	0.837	448	6 640
No. 244	−0.2	13.3	13.2	0.805	0.800	740	7 820
No. 117	−0.13	13.0	13.5	0.851	0.854	475	4 060
No. 2	no change	13.0	13.0	0.823	0.823	705	6 875
No. 246	no change	13.0	13.1	0.817	0.824	993	7 855
No. 108	−0.2	12.8	13.2	0.820	0.800	685	5 180
No. 66	−0.1	12.7	13.0	0.870	0.849	276	4 520
No. 184	−0.15	12.8	13.3	0.830	0.802	690	4 445
No. 74	−0.2	12.7	12.7	0.813	0.823	375	5 850
No. 238	−0.1	12.4	12.4	0.797	0.790	397	6 400
No. 11	−0.16	12.0	13.1	0.809	0.784	680	4 625
No. 91	no change	12.4	12.2	0.768	0.795	730	5 885
No. 239	−0.1	12.2	12.5	0.796	0.780	875	7 010
No. 60	no change	11.5	11.7	0.800	0.802	568	7 300
No. 127	−0.1	11.5	11.9	0.806	0.814	464	7 240
No. 6	−0.7	11.4	12.1	0.790	0.783	724	5 700
No. 3	−0.15	11.3	11.2	0.763	0.762	257	2 900
No. 242	no change	11.1	11.1	0.767	0.762	605	5 150
No. 210	no change	11.0	11.7	0.781	0.753	228	6 800
No. 241	no change	10.9	11.0	0.769	0.764	1 065	10 220
No. 236	no change	10.8	10.9	0.767	0.744	397	4 335
No. 240	−0.14	10.6	10.8	0.762	0.788	595	8 500
No. 243	−0.1	10.4	11.1	0.754	0.739	341	8 205
No. 283	no change	10.1	10.7	0.738	0.722	842	6 165
No. 247	−0.08	9.8	10.0	0.738	0.739	1 130	7 220
No. 37	no change	9.5	9.3	0.754	0.765	315	9 600
No. 4	−0.04	9.2	9.3	0.732	0.650	671	8 825
Type No. 2							
No. 182	−0.4	17.4	17.3	0.864	0.863	1 140	3 090
No. 193	−0.2	16.3	16.8	0.860	0.866	840	2 925
No. 248	−2.4	16.2	16.8	0.834	0.843	88	2 425
No. 251	..	15.9	....	0.876	This brick disintegrated, cracked into fragments.		
No. 53	−0.1	16.0	16.3	0.865	0.862	1 088	5 620
No. 198	..	15.8	....	0.859	This brick was completely disintegrated.		
No. 81	−0.2	15.6	15.6	0.814	0.821	540	3 410
No. 84	−0.5	15.5	15.7	0.822	0.816	600	2 460
No. 67	−0.15	15.3	15.3	0.810	0.810	803	3 180
No. 90	−0.2	15.3	15.3	0.816	0.820	361	3 165
No. 96	..	15.1	....	0.825	This brick was completely disintegrated.		
No. 47	−1.0	15.0	14.7	0.817	0.800	249	3 045
No. 88	..	14.9	....	0.825	This brick was completely disintegrated.		
No. 306	no change	14.8	15.0	0.821	0.828	1 090	5 890

TABLE II.—TESTS OF GROUP II BRICKS OF FOUR TYPES—(*Continued*)

All Bricks Subjected to 100 Freezing-and-Thawing Cycles

Specimen	Change in Weight, per cent of Original Dry Weight	Absorption by Boiling Prior to Freezing-and-Thawing Tests, per cent of Initial Dry Weight	Absorption by Boiling After Freezing-and-Thawing Tests, per cent of Final Dry Weight	Ratio, Cold Absorption Divided by Boil Absorption Prior to Freezing-and-Thawing Tests	Ratio, Cold Absorption Divided by Boil Absorption After Freezing-and-Thawing Tests	Modulus of Rupture After 100 Freezing-and-Thawing Tests, lb. per sq. in.	Compressive Strength (flat) After 100 Freezing-and-Thawing Tests, lb. per sq. in.
TYPE No. 2—(*Continued*)							
No. 7	−0.3	14.7	15.0	0.800	0.798	665	2 850
No. 89	..	14.9	....	0.820	This brick was completely disintegrated.		
No. 244	..	14.5	....	0.816	This brick was completely disintegrated.		
No. 26	−1.2	14.6	14.5	0.801	0.802	137	3 670
No. 49	..	14.2	....	0.804	This brick was completely disintegrated.		
No 28	−1.5	15.1	15.4	0.814	0.810	126	2 575
No. 86	−0.4	15.0	15.5	0.820	0.822	115	2 740
No. 60	−0.1	13.6	14.1	0.804	0.803	990	4 020
No. 222	..	13.0	....	0.794	This brick was completely disintegrated.		
No. 161	no change	13.0	12.5	0.807	0.807	870	4 950
No. 200	−1.7	14.1	14.4	0.796	0.799	164	3 400
No. 191	−0.4	13.8	14.2	0.775	0.801	870	3 840
No. 184	−0.9	13.0	13.1	0.796	0.798	145	3 762
No. 27	..	12.8	....	0.800	This brick was completely disintegrated.		
No. 66	no change	12.8	12.8	0.798	0.796	1 020	4 860
No. 37	no change	12.9	13.4	0.800	0.797	1 060	4 880
No. 44	−0.1	12.9	12.9	0.794	0.797	1 000	4 820
No. 159	−0.2	12.7	12.8	0.795	0.792	927	3 960
No. 2	no change	12.6	12.6	0.786	0.781	882	4 710
No. 36	−0.3	12.7	12.7	0.796	0.796	1 150	3 990
No. 30	−0.4	12.5	12.6	0.771	0.767	680	3 850
No. 78	..	12.5	....	0.800	This brick was completely disintegrated.		
No. 1	−0.7	12.4	12.4	0.766	0.744	178	4 705
No. 54	−0.2	11.9	12.1	0.745	0.748	845	5 040
No. 20	no change	11.7	11.8	0.744	0.738	1 040	5 875
No. 21	−0.1	11.7	11.9	0.743	0.735	1 155	5 550
No. 3	+0.15	11.8	11.7	0.755	0.755	1 250	5 025
No. 11	−0.1	11.8	12.1	0.760	0.749	1 120	4 500
No 10	no change	11.6	12.0	0.751	0.751	672	4 130
TYPE No. 3							
No. 509	−0.1	9.8	10.1	0.760	0.758	1 960	14 935
No. 508	−0.15	9.1	9.3	0.756	0.750	2 175	16 885
No. 213	−0.14	8.6	8.7	0.737	0.750	1 455	6 845
No. 135	−0.2	7.9	8.0	0.742	0.742	1 520	17 345
No. 269	−0.3	7.5	7.6	0.717	0.702	2 300	13 025
No. 116	−0.1	7.6	7.7	0.700	0.694	1 840	11 515
No. 216	−0.1	7.4	7.6	0.700	0.689	1 870	9 480
No. 336	no change	7.4	7.6	0.702	0.705	2 300	11 115
No. 121	+0.1	7.3	7.4	0.690	0.701	2 130	8 265
No. 196	−0.15	7.3	7.5	0.663	0.659	1 980	10 900
No. 188	−0.2	7.2	7.3	0.665	0.663	2 185	10 545
No. 157	−0.1	7.0	7.3	0.647	0.646	1 540	9 215
No. 89	−0.2	7.0	7.2	0.658	0.656	1 835	10 925
No. 221	no change	7.0	7.1	0.700	0.701	2 435	12 300
No. 90	−0.14	6.9	7.1	0.677	0.646	2 725	15 190
No. 244	+0.12	6.7	6.8	0.673	0.677	2 140	12 790
No. 320	−0.15	6.6	6.8	0.679	0.671	2 175	11 825
No. 248	no change	6.6	6.9	0.673	0.656	632	9 550
No. 243	+0.2	6.5	6.7	0.653	0.647	2 580	12 415
No. 189	−0.15	6.5	6.9	0.662	0.651	2 390	9 175
No. 77	−0.2	6.4	7.0	0.655	0.646	2 475	8 650
No. 199	−0.1	6.3	6.4	0.638	0.643	2 255	14 720
No. 222	−0.13	6.3	6.5	0.658	0.653	3 080	15 635
No. 161	−2.1	6.3	6.4	0.640	0.643	2 430	10 200
No. 112	−0.15	6.4	6.6	0.651	0.647	1 730	12 380

TABLE II.—TESTS OF GROUP II BRICKS OF FOUR TYPES—(*Continued*)

All Bricks Subjected to 100 Freezing-and-Thawing Cycles

Specimen	Change in Weight, per cent of Original Dry Weight	Absorption by Boiling Prior to Freezing-and-Thawing Tests, per cent of Initial Dry Weight	Absorption by Boiling After Freezing-and-Thawing Tests, per cent of Final Dry Weight	Ratio, Cold Absorption Divided by Boil Absorption Prior to Freezing-and-Thawing Tests	Ratio, Cold Absorption Divided by Boil Absorption After Freezing-and-Thawing Tests	Modulus of Rupture After 100 Freezing-and-Thawing Tests lb. per sq. in.	Compressive Strength (flat) After 100 Freezing-and-Thawing Test, lb. per sq. in.
			TYPE No. 3—(*Continued*)				
No. 145	no change	6.4	6.3	0.627	0.630	2 585	13 335
No. 136	−0.3	6.3	6.4	0.634	0.625	1 780	12 500
No. 203	+0.1	6.1	6.3	0.645	0.643	3 045	14 845
No. 179	−0.15	6.1	6.5	0.636	0.626	2 625	10 400
No. 231	no change	6.1	6.2	0.636	0.640	2 545	12 410
No. 151	+0.2	6.1	6.1	0.636	0.620	1 380	7 900
No. 242	−0.15	6.3	6.5	0.653	0.653	2 060	11 225
No. 237	no change	6.2	6.5	0.639	0.642	2 090	9 510
No. 149	no change	5.9	6.1	0.627	0.645	2 450	13 205
No. 110	no change	5.9	6.1	0.619	0.619	2 580	12 520
No. 281	−0.2	5.8	6.1	0.560	0.556	2 130	13 900
No. 235	+0.1	5.7	5.9	0.617	0.610	2 820	10 370
No. 180	−0.3	5.7	5.7	0.606	0.623	2 045	13 515
No. 75	+0.2	5.8	5.8	0.619	0.619	2 445	16 225
No. 232	−0.3	5.5	5.5	0.630	0.638	2 000	14 090
No. 165	no change	5.5	5.5	0.638	0.648	2 275	12 995
No. 200	no change	5.4	5.6	0.586	0.597	1 810	7 315
No. 140	+0.1	5.2	5.2	0.585	0.600	2 600	15 405
No. 292	no change	4.8	4.9	0.577	0.558	3 355	15 910
No. 142	no change	4.6	4.8	0.559	0.561	2 550	15 005
No 227	−0.15	4.8	5.1	0.600	0.588	2 510	13 635
			TYPE No. 4				
No. 135	−0.1	10.3	10.4	0.620	0.649	698	8 145
No. 100	+0.2	10.7	10.7	0.609	0.606	1 485	9 475
No. 153	−0.05	10.1	10.1	0.639	0.636	977	10 580
No. 93	−0.15	9.3	9.0	0.596	0.644	1 120	10 700
No. 17	−0.25	9.3	9.4	0.594	0.631	1 520	13 350
No. 90	−0.15	8.7	9.2	0.584	0.585	1 004	13 630
No. 145	−0.2	8.4	8.7	0.571	0.567	1 760	13 950
No. 128	−0.15	8.4	8.8	0.566	0.566	1 510	11 400
No. 109	−0.05	8.0	8.5	0.566	0.577	1 740	14 300
No. 57	−0.15	7.8	8.1	0.556	0.570	1 018	14 080
No. 13	−0.1	7.7	7.9	0.572	0.582	1 455	11 770
No. 81	no change	7.7	7.7	0.566	0.607	1 750	16 300
No. 198	no change	7.7	7.8	0.545	0.544	1 130	2 332
No. 83	no change	7.6	7.5	0.557	0.590	918	12 720
No. 45	−0.1	7.6	7.6	0.538	0.542	1 600	14 750
No. 148	+0.1	7.6	7.8	0.535	0.548	2 440	13 990
No. 179	no change	7.4	7.5	0.525	0.541	850	15 835
No. 102	−0.1	7.3	7.3	0.532	0.573	2 110	14 550
No. 133	no change	7.3	7.5	0.516	0.509	1 700	12 000
No. 36	+0.9	7.2	7.5	0.516	0.438	1 470	14 845
No. 125	−0.1	7.1	7.5	0.577	0.564	1 615	11 000
No. 106	no change	7.1	7.1	0.531	0.531	1 445	17 000
No. 142	+0.05	7.1	7.3	0.518	0.515	1 200	16 940
No. 113	−0.1	7.0	7.2	0.523	0.506	1 795	12 650
No. 124	+0.05	6.9	7.0	0.531	0.549	2 445	13 990
No. 126	−0.15	7.0	7.4	0.519	0.516	1 425	12 950
No. 138	−0.25	6.8	6.7	0.477	0.474	1 370	11 425
No. 147	−0.05	6.6	6.9	0.519	0.516	1 540	15 100
No. 28	−0.25	6.7	7.4	0.510	0.463	965	14 640
No. 137	−0.05	6.4	6.4	0.517	0.525	1 670	14 245
No. 26	−0.3	5.8	5.6	0.477	0.500	1 430	14 500
No. 144	−0.2	5.8	5.9	0.475	0.458	1 470	13 420
No. 104	−0.2	5.8	6.3	0.473	0.457	1 200	6 000
No. 46	−0.05	5.6	5.5	0.500	0.488	1 245	13 840
No 114	−0.15	5.6	5.8	0.467	0.480	900	13 550
No. 143	−0.2	5.2	4.0	0.419	0.423	1 310	16 430

TABLE III.—SUMMARY OF STRENGTH DATA FROM TABLES I AND II.

	Sub-Group[1]	Number of Bricks	Absorption by Boiling (Before Freezing), per cent of Dry Weight		Average Modulus of Rupture, lb. per sq. in.	Average Compressive Strength (flat), lb. per sq. in.	Remarks
			Range	Average			
Type No. 1	I-a	20	14.6 to 12.0	12.9	551	5 357	Very slight loss in modulus of rupture and compressive strength
	II-a	23	15.0 to 12.0	13.3	520	5 295	
	I-b	22	Below 12.0	11.2	700	6 707	Group II lower in modulus of rupture and higher in compressive strength than Group I
	II-b	14	Below 12.0	10.6	586	7 011	
Type No. 2	I-a	32	16.1 to 14.0	15.7	769	3 521	Group II distinctly lower in both modulus of rupture and compressive strength than Group I
	II-a	21	16.3 to 14.0	15.2	425	2 255	
	I-b	17	Below 14.0	13.0	1 055	4 544	Group II distinctly lower in both modulus of rupture and compressive strength
	II-b	21	Below 14.0	12.6	797	3 927	
Type No. 3	I-a	34	7.5 to 6.5	7.1	2 059	14 551	Group II slightly lower in compressive strength than Group I
	II-a	15	7.5 to 6.5	7.0	2 081	11 114	
	I-b	13	Below 6.5	5.9	2 179	14 686	Group II lower in compressive strength than Group I
	II-b	26	Below 6.5	5.8	2 372	12 608	
Type No. 4	I-a	26	9.9 to 7.5	8.2	1 155	13 085	Group II even higher in modulus of rupture than Group I
	II-a	14	10.1 to 7.5	8.3	1 510	13 058	
	I-b	18	Below 7.5	6.6	1 402	13 563	Groups I and II have about the same strengths
	II-b	20	Below 7.5	6.6	1 458	13 746	

[1] Subgroups designated "a" represent those bricks of Groups I and II in the higher range of absorption; those designated "b" represent bricks in the lower range of absorption.

NOTE.—In comparing specimens of Group I (not frozen and thawed) with those of Group II (frozen and thawed) it is best to compare with brick having the same or very nearly the same degree of absorption. Accordingly, Group II specimens whose percentages of absorption were outside the limits of the range stated in the table have not been included in the comparisons. For example, the first five specimens of Group II, Type No. 1 (see Table II) have absorptions of 15.5, 15.3, 15.1, 15.1 and 15.1, respectively. All of these percentages are higher than the highest percentage absorption among specimens of Group I of this type of brick. Consequently, in arranging Table III, these five brick have been omitted from the averages.

TABLE IV.—SUMMARY OF STRENGTH DATA FROM TABLE III.

	Designation by Range of Absorption[a]	Differences Between Averages of Subgroups, per cent of Average for Subgroup of Group I The values are negative if average for subgroup of Group I is higher than that of sub-group of Group II, and positive if the reverse is the case	
		Percentage Differences in Modulus of Rupture	Percentage Differences in Compressive Strength (flat)
Type No. 1..........................	A_1	−5.63	−1.16
	A_2	−16.28	+3.04
Type No. 2..........................	A_1	−44.73	−37.94
	A_2	−24.45	−13.58
Type No. 3..........................	A_1	+1.07	−23.62
	A_2	+8.85	−14.15
Type No. 4..........................	A_1	+30.73	−0.21
	A_2	+3.99	+1.34
Average of differences for the four types, designation A_1....		−4.64	−15.76
Average of differences for the four types, designation A_2....		−6.97	−5.84

[a] A_1 represents bricks of higher range of absorption, corresponding to Subgroups I-a and II-a in Table III. A_2 represents bricks of lower range of absorption, corresponding to Subgroups I-b and II-b in Table III.

The data for each brick should be considered separately. In order that this may be done conveniently, Table III may be further condensed and rearranged. Designating each pair of subgroups in the higher range of absorption (I-a and II-a) as A_1 and each pair in the lower range of absorption (I-b and II-b) as A_2, Table IV is arranged.

Considering the data as a whole, it is noted from comparison of the averages in Table IV that the more absorptive bricks actually made a better showing than those of lower absorption in the flexure tests after the 100 cycles of freezing and thawing; although the two averaged per cent losses in modulus of rupture, 4.64 per cent for A_1 and 6.97 per cent for A_2, are so nearly the same that it would not be far wrong for practical purposes to consider them equal.

However, this is not the case when the compressive strengths are considered. Here, the average per cent loss after 100 freezing-and-thawing cycles among the more absorptive brick (designated A_1) is about three times that of those in the lower range of absorption (A_2), being 15.76 per cent in the former and 5.84 per cent in the latter case.

Consider again the data for each type of brick separately. In the case of type No. 1 bricks, made from surface clay and molded dry-press, those bricks relatively low in absorption (A_2) decreased more in flexural strength than did those of higher absorption (A_1). The reverse is the case when the compressive strengths are compared. In the case of type No. 2 bricks, the greater weakening both in the compression and flexure tests is seen to be characteristic of the specimens of higher absorption. This fact is apparently in agreement with the opinion often expressed that bricks of higher absorption are less capable of withstanding the freezing and thawing of moisture within them.

The data pertaining to the stiff-mud, side-cut shale brick (types Nos. 3 and 4) are even more anomalous. Thus, from an inspection of Tables III and IV, it will be seen that the average modulus of rupture of bricks of type No. 4 of the higher absorption range after 100 cycles of freezing and thawing (II-a) is greater than that for those not frozen and thawed (I-a). Similarly, bricks of this type of lower absorption had an average modulus of rupture greater by 4 per cent after freezing and thawing. There is very little difference in the case of bricks of this type between averages of the compressive strengths before and after freezing and thawing.

The "weathered" bricks of type No. 3 are seen to have diminished in compressive strength and this is the case throughout the entire range of absorption for this brick. However, in spite of this decrease, it may be noted from the actual figures in Table II for this type that the compressive strengths of the bricks which endured 100 cycles of freezing and thawing are as high as could be ordinarily desired of brick fresh from the producer.

An Apparent Anomaly:

Brick of type No. 2 has a property that is also apparently possessed by certain other makes. A brick of this type under-burned to an extent such that it will begin to disintegrate after ten freezing-and-thawing cycles may actually be lower in absorption than one which endures 100 cycles without disintegrating. During this investigation, tests were made on one other make of brick of this type, the data for which are omitted here since no strength measurements were made.

Lovejoy's[1] "settle" curves show that among certain clays fired in commercial kilns for a period of days. there was a slow and fairly constant rate of shrinkage during the first six days. This was then followed by a volume increase which continued until the ware had been fired for eight days. Between the eighth and ninth day, there was again a slight shrinkage, and from the ninth day to the finish of the burn the shrinkage was rapid. It is difficult to conceive of an increase in bulk volume of a clay body of constant mass without there being a simultaneous increase in the apparent porosity. Therefore, among the clays studied by Lovejoy, brick which were very decidedly under-burned during the first five days in the kiln were actually lower in absorption than those fired for eight days at a constantly increasing temperature.

J. M. Knote[2] is essentially in agreement with these data of Lovejoy. He found the porosity of certain fire-clay bodies did not change appreciably in their apparent porosities during the temperature range 550 to 1050° C. It is well known that certain building bricks are made from what is essentially fire clay.

The materials submitted by a manufacturer for tests by a laboratory are usually of the more marketable variety. It is therefore possible that many who have studied the absorption of brick, tile, etc., as related to their other properties have never observed instances of the fact described above, that is, a distinctly under-burned clay body may actually be no higher (in some cases lower) in absorption than it would be when it is more marketable and serviceable. Whether or not this condition is very rare, is not the point. Since not much is known about it, it deserves further study and consideration.

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[1] Ellis Lovejoy, "Note on Settle Records," *Transactions*, Am. Ceramic Soc., Vol. 7, Part III, p. 422 (1905).

[2] J. M. Knote, "Some Physical and Chemical Changes in Clays, Due to Heat," *Transactions*, Am. Ceramic Soc., Vol. 12, p. 226 (1910).

Disintegration:

It may be noted (Table II) that the loss in weight during the weathering tests was in most cases very small. Certain bricks of type No. 2 which disintegrated during these tests are, however, very notable exceptions. This type of brick was characterized by the presence of an unusually high percentage of free lime, that is, lime contained as the oxide, CaO. The oxide hydrates to $Ca(OH)_2$, the latter being slightly soluble. Continued leaching of this hydrated lime during the thawing process tended to progressively dissolve out this lime, thereby weakening the structure of the brick to some extent. Such leaching action was evident from visual inspection; after the 100 cycles, lime was accumulated near the surfaces. Some of this slowly carbonated and this reaction was of course attended by a volume increase in the lime material. It is necessary to differentiate between such chemical reactions and the more common process, crystallization of salts. This reaction may have induced stresses, causing thereby more or less disintegration. However, it is worth while to compare the data in Tables I and III for many individual specimens of type No. 2, Group I, with similar data for specimens of the same brick of Group II. It will be noted that the strength of many individual specimens of the same degree of absorption in these two groups compare favorably, that is, in these individual instances it does not appear that there was any noticeable weakening during the 100 cycles. This fact is, of course, obscured by considering only the averages for both groups. Most of the bricks that were completely disintegrated are in the higher absorption range.

Changes in Pore Ratios:

H. G. Schurecht[1] has defined "pore ratio" as the percentage absorption (computed on the basis of the dry weight of the specimen) during 48 hours of total immersion of the specimen in water at room temperature, divided by the percentage absorption during immersion of the specimen for 5 hours in boiling water. These values appear in Table II, as the ratios of absorption by cold immersion to absorption by boiling, both before and after freezing and thawing. It is seen that the pore ratios of the specimens usually were changed by freezing and thawing—in many cases appreciably. These data are summarized in Table V.

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[1] Unpublished data.

There were a few more instances of decrease than of increase in the pore ratio, but the two are nearly equally divided. It is further noted from Table II that the absorption by boiling after 100 cycles of freezing and thawing was in most cases greater than that of the same specimens prior to freezing and thawing; there are only 13 instances out of 167 in which the absorption was decreased by freezing and thawing. In most of these instances the decreases are slight and within experimental error. Since the pore ratio was increased in a number of specimens very nearly equal to that number wherein it was decreased, it is seen that the absorption by immersion at normal room temperature was increased relatively less than the boiling absorption in about one-half of the specimens and relatively more in the other one-half that were subjected to freezing and thawing. Therefore, in general, the apparent porosities of the specimens were increased and the pore ratios were altered by the weathering tests.

TABLE V.—SUMMARY OF DATA ON PORE RATIOS FROM TABLE II.

	Number of Bricks Whose Pore Ratios were Increased	Number of Bricks Whose Pore Ratios were Decreased	Number of Bricks Whose Pore Ratios Remained Unchanged	Maximum Change in Pore Ratio
Type No. 1	16	24	2	−0.082
Type No. 2	12	16	5	−0.029
Type No. 3	17	25	4	−0.031
Type No. 4	20	14	2	+0.048
Average	16	20	3	−0.024

SUMMARY AND CONCLUSIONS

1. A number of representative bricks of four different types, made from clay and shale, have been subjected to 100 alternate freezing-and-thawing cycles while saturated.

2. The moduli of rupture and compressive strengths of these bricks, determined subsequent to the cycles of freezing and thawing, have been compared with similar data obtained with other representative lots of the same types of brick obtained from the same manufacturers, having the same degrees of absorption but which were not subjected to freezing and thawing.

3. Freezing and thawing tended to reduce the compressive strengths of the bricks in all cases, but to a more noticeable extent among those bricks of the higher absorption range. This was true both for bricks made from shale and from surface clay.

4. The bricks were weakened relatively less in flexural than in compressive strength by the exposures to freezing and thawing.

5. Freezing and thawing also tended to increase the extent of absorption of the bricks in nearly all cases.

6. The Schurecht ratio (pore ratio) of nearly all of the bricks exposed was noticeably changed, being increased and decreased in about an equal number of cases.

7. The loss in weight of the specimens subjected to these severe tests was very small for three of the types of brick. There were noticeable losses in weight and disintegration in over 20 per cent of the bricks of the fourth type. It is believed that the presence of considerable quantities of uncombined lime in these bricks contributed to their disintegration.

8. From the results obtained, there is no evidence that is in conflict with the belief that absorption is not a reliable index to the weather resistance of brick made from clay or shale.

DISCUSSION

MR. L. B. LENT[1] (*presented in written form*).—This excellent paper by Mr. Palmer and Mr. Hall is a welcome and valuable aid in the work of the Society's Committee C-3 on Brick. I think it was Josh Billings who, a long time ago, said that "a lot of people know a lot of things that ain't so." This paper, and that presented last year by McBurney,[2] constitute pretty conclusive proof that one of our past beliefs is "not so." The data shows that absorption percentage is *no* measure of weathering resistance, as had been the widespread belief of the past many years.

Committee C-3 should be grateful to the authors of this paper, and to McBurney and others, who have furnished this justification of the committee's action in omitting absorption requirements in the present standard specifications for clay building brick. The committee's conviction that absorption requirements were meaningless and perhaps misleading is now confirmed.

Let us hope that further research will furnish us with some laboratory measure of weathering.

I should like to ask the authors if they believe that 100 cycles of freezing and thawing of *whole bricks* closely represent conditions of actual exposure in brick structures; and does this test furnish an accurate measure of the weathering resistance of brick masonry?

MR. A. E. R. WESTMAN.[3]—I should like to comment on one point in connection with a material such as brick, namely, that the producer of materials which vary unavoidably in quality is at present at the mercy of the inevitable laws of chance and may have his product condemned on the basis of an insufficient sample. That situation is one with which the Technical Committee on Presentation of Data of the Society's Committee E-1 on Methods of Testing is concerned, and if we can persuade the various committees and authors to present their data in accordance with the methods we have developed, it should be possible finally to draw up our standards and specifications so that the risk which the producer takes of having his products wrongly condemned when submitted for test will be as low as possible. As a general thesis, I might say that modern investigation demands that any conclusion at the end of a paper be subject to the criterion: Can the results be explained wholly on the basis of chance? If they can, then the conclusion requires more proof.

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[1] Chief Engineer, Common Brick Manufacturers' Assn. of America, Cleveland, Ohio.

[2] J. W. McBurney, "The Water Absorption and Penetrability of Brick," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 711 (1929).

[3] Ontario Research Foundation, Toronto, Ont., Canada.

MR. L. E. KERN.[1]—We have been told that a number of things we thought were true are not true. I am wondering if we can now expect the scientist to tell us the things that are true about brick. We all know that brick is a reliable building material. Nevertheless, we do occasionally have trouble. It may be disintegration, but if you look around you will see brick everywhere and you will see very little disintegration. We are troubled with dampness in walls, and we are troubled with efflorescence. They seem to be the two weaknesses that are inherent in brick. Now, we learn that the absorption of brick is not a measure of the dryness of a wall. We learn that efflorescence is caused by dampness. There are two things that I think the Committee on Brick should work on—some way whereby we may with assurance build a brick wall and know in advance that it will be dry and that there will be no efflorescence.

MR. L. A. PALMER.[2]—With reference to Mr. Kern's remarks we must all realize that mortar and brick are being today thrown together haphazardly. In the first place there is often poor workmanship and in the second place the science of using the proper cementing material with a masonry unit of known properties has never been developed. In fact not many have ever considered that this very important subject should be studied.

Replying to Mr. Lent, it is very difficult to duplicate in the laboratory actual weathering conditions. If a guess is acceptable, it may be said that the 100 cycles of freezing and thawing may be equivalent to thirty years of outdoor exposure of the brick in the severest kind of climate and without protection of any sort such as overhanging eaves, etc. This supposition is, I believe, offered by Mr. S. H. Ingberg, of the Bureau of Standards. This may answer Mr. Lent's question.

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[2] Research Associate of the American Face Brick Association at the U. S. Bureau of Standards, Washington, D. C.

STRENGTH TESTS ON ROOF TILES

By Norman W. Kelch[1]

Synopsis

Burnt-clay roofing tiles are primarily a water-resistive covering for a roof. When such roofs are so located that the fall of a broken or loosened tile would endanger life or limb below, then the quality and security of the roofing tiles become a matter of legislation for public safety. The object of this investigation was to determine a fair and adequate method of testing roofing tiles which would truly indicate their quality with respect to probable permanency and security, bearing in mind the thought that the test method should be one which could be incorporated in building codes.

Pieces cut from tile similar in size to those used in testing slate were found to be difficult to prepare for test, as well as difficult to calculate modulus of rupture due to the curvature of the tile. Small pieces, essentially cubes, cut from a single tile and tested in direct compression after extreme care was taken in preparation showed values varying 300 per cent.

Another method tried was embedding the down-turned edges of a tile solidly in plaster of Paris to obtain uniform bearing, with load applied to a bar embedded in plaster of Paris along the top longitudinal center line the full length of the tile. Slight variations in the width of the top bedding on identical tile showed wide variations in results. The method found most satisfactory was by all odds the simplest and consisted of supporting a curved type tile on its down-turned edges on supports 5 in. each side of the center of the tile applying a concentration on top at the center. With this method results were checked and rechecked with extreme accuracy and satisfaction.

Description of Types of Roofing Tile

In California there are three general types of roofing tile in use: the two-piece Mission, the one-piece Spanish and the flat English or shingle.

The two-piece type, illustrated in Fig. 1 (*a*), consists of pans and covers, or bottoms and tops, made with either a straight barrel or a tapered barrel. The pans may or may not be identical in shape and size with the covers. In the tapered type the pans are laid reverse to the covers, that is, with the large end up and small end down the slope.

The one-piece Spanish tile, illustrated in Fig. 1 (*b*), is a combination bottom and top tile made in two patterns, one having a straight barrel for the cover integral with a flat pan which has an upturned flange to form the under lap for the tile laid adjacent. The other

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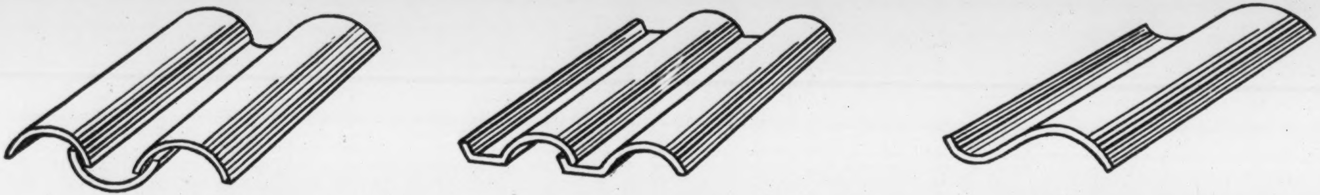
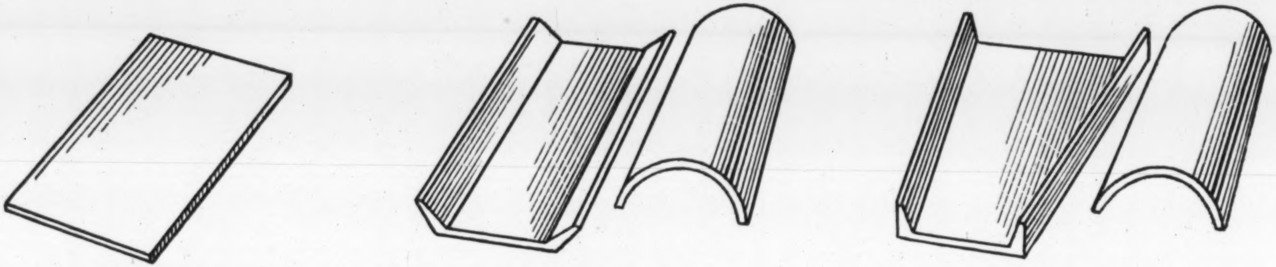


(*a*) Two-piece Mission, straight barrel tile.

(*b*) One-piece Spanish flat pan tile.

(*c*) One-piece Spanish "S" tile.



(*d*) Flat English or shingle tile.

(*e*) Italian pan tile, flanges at obtuse angle.

(*f*) Italian pan tile, flanges at 90-deg. angle.

FIG. 1.—Showing Types of Roofing Tile.

pattern is simply a cover with a reverse cover made integral forming the pan, so that a cross-section of the tile forms a letter "S." It is therefore known as the Spanish "S" type, and is illustrated in Fig. 1 (*c*).

The flat English or shingle type, illustrated in Fig. 1 (*d*), is made in true shingle shapes and sizes; however, some have an integral lug extended across the upper end so as to hook over wood strips to which the tile is fastened. Included in the flat types are flat pans with side flanges for underlap extending upward either at a steep angle as shown in Fig. 1 (*e*) or perpendicular as shown in Fig. 1 (*f*). These are usually referred to as Italian flat pans.

PURPOSE OF TESTS

Fundamentally, successful roofing tiles must effectively shed water and resist disintegration due to weathering. Secondly, they must successfully withstand physical strains caused by persons walking on roofs to clean gutters, fix flashings, radio aerials or what not, and must resist breaking by high winds tending to lift or overturn them from their fastenings. Adverse performances of poorly made or underburned roofing tiles have at times not only reflected upon the reputation of good roofing tile but have constituted a hazard to life and limb. Municipal building departments have been alert to the latter situation and have sought to include in their building ordinances a provision for the quality and application of roofing tiles as a measure of public safety.

In order to set up a minimum requirement for the quality and application of roofing tile it was first necessary to set up a method of testing, next to study the range of results, and finally to designate a minimum requirement for safety. To accomplish this was the purpose of this investigation.

Flat type tiles are usually laid on roofs of relatively steep pitch and are thus seldom walked upon and are of such shape and lay that high winds can not easily displace them.

Curved type tiles are laid on relatively low pitched roofs, many of which have a 4 in. rise in a 12 in. run (one-sixth pitch) and occasionally a 3 in. rise in a 12 in. run (one-eighth pitch). In such cases they are subjected to the aforementioned strains. For these reasons particular attention was given to the strength of the curved type tile although some tests and observations were made upon the flat types.

SELECTION OF SPECIMENS

Tiles were selected as being the range of tile delivered to jobs by both good and poor manufacturers, many hundreds being tested.

FIRST METHODS OF TESTING

Curved type specimens, as in Fig. 1 (*a*), were laid on a steel table edges down, and the edges were cast in plaster of Paris to obtain true bearing; a plaster-of-Paris bed was laid along the top longitudinal center line the full length of the tile and a flat uniform bearing surface was provided about 2 in. wide upon which a uniform load was applied. The top bearing bed was slightly reduced in width on some specimens of apparent similarity, and marked differences in strengths were noted, which might, of course, be expected. In such a procedure it was difficult to arbitrarily set a width of bearing because of the varying widths of tiles. Also, the bedding of the bottom flanges or sides of the tile would, under pressure, develop some frictional resistance on the bearing plate which would be difficult to hold constant. Also it would be difficult to determine a minimum safety load under such a test because of the various sizes of tiles.

Other specimens were placed against a grinding stone and the bearing sides of the tile were ground flush and smooth so that the down-turned edges did not require bedding, although the longitudinal bearing was bedded as before. It was quite difficult to grind these sides or edges to an absolute even bearing and the process required considerable time. Considering the difficulties surrounding the preparation of the test specimens this method was discarded.

SECOND METHODS OF TESTING

In considering the application to roofing tiles of the standard tests as prescribed for slate, it was observed that some roofing tiles vary in their thickness from end to end and in their cross-section according to type. Also that roofing tiles are made both by machinery and by hand. In the hand-made tile if there were molding seams apparent from the filling in of clay by hand, these seams of weakness could be avoided in taking a strip specimen and the test would not be fair or true. Also the curves of the cross-section, some being concentric and others eccentric, would make the calculation of the modulus of rupture extremely difficult on so small a cross-section. It seemed, therefore, unwise to endeavor to develop a test method along this line.

Believing, however, that the compressive strength of the burned clay itself might be a true index to the strength of the tile, small pieces, for simplicity called cubes, were cut from tiles and tested on end grain.

A piece 1 by 1 in. was cut from each of two tiles previously ruptured. Since the piece was curved, there was but one way to compress it, on end. The pieces required extremely careful effort and considerable time to rub them down to a full-surface absolute bearing area. A minute high or low spot on so small a piece would greatly affect its resistance, as was seen later. These first results were as follows:

RUPTURE STRENGTH OF TILE, LB.	COMPRESSIVE STRENGTH, LB. PER SQ. IN.
640	8230
330	6950

From this showing there were prepared from each of five tiles, previously ruptured, three pieces, 1 in. square: these were sawed out with a fine carborundum wheel and the surfaces obtained were perfect to the touch, but when rubbed on a steel plate they showed black high spots. To rub these down was thought too laborious from the previous experience, so they were capped with cement and plaster of Paris. When hard set these cappings also showed minute high spots which were rubbed down considerably by hand to effect as perfect a contact bearing as possible. The preparation of the specimens for what is termed a cube test (although not a true cube, being 1 by 1 in. by thickness of tile) was very laborious, and accordingly expensive. The results will be discussed later.

RUPTURE OF WHOLE TILES

The most valuable knowledge gained from a laboratory test is that obtained from a test which measures the value of a specimen by reproducing as nearly as possible the conditions in its field of service.

In considering this it was appreciated that a roofing tile as laid on a roof never has a uniformly solid bearing, either upon its edges or top roll, but usually has a bearing of three or more points of contact. To simulate such a condition the use of standard testing edges immediately suggested itself. Edges were used having about a 1-in. radius edge with their bases placed tight together giving a center to center span of 5 in.; the transverse center line was described upon the tile and the tile centered on the span and a steel pin 2 in. in diameter was laid across the tile at the center to which the load was applied. The down-turned edges were shimmed with steel blades to provide four points of support for the tile. This method might well be considered to duplicate the actual condition of a tile laid on a roof with a load applied to its center point, except possibly as to the length of span. The span was increased to 12 in. and comparisons noted.

The 12-in. span is perhaps more nearly a field condition than the 5-in. span. The results are discussed later.

Many tiles were subjected to the 5-hour boiling test for percentage of absorption. We found, as others have found, that absorption alone is not an indication of the strength of a burnt-clay product. A few of the results from different makes of tile follow:

THICKNESS, IN.	ABSORPTION, PER CENT	RUPTURE STRENGTH, LB. PER SQ. IN.
$\frac{7}{16}$	12.83	460
$\frac{1}{2}$	13.87	140
$\frac{1}{2}$ and $\frac{1}{4}$	15.53	780
$\frac{9}{16}$	18.54	550

To limit a tile to a maximum absorption alone as an index to strength appears at this time to be erroneous. However, Schurecht's ratio of absorption may be an indication as to weather resistance and possibly underburning.

As to percentage of absorption alone indicating durability, it might be observed here that in the Geological Survey of Ohio, *Bulletin No. 11*, 1910, is recorded some percentages of absorption of old roof tiles in that locality. Tiles on a roof still doing good service after 75 years showed from 12.76 to 14.69 per cent absorption (the same clay); on one roof 92 years old, and still in good condition, the tiles showed from 7.17 to 21.46 per cent absorption (the same clay). In that bulletin it is stated that porosity of the tile does not seem to reduce its resistance to freezing and other elements. It would be interesting to test some of the tiles several hundred years old both for water absorption and for strength, by the method of rupture herein described.

RESULTS OF TESTS

Compression Results:

The actual compression of the 1-in. square pieces was a very simple operation in the testing machine. The fact learned was that in a set of three pieces cut adjacently from the same tile and prepared in the identical manner as nearly as possible with hand and eye accuracy, the results showed the maximum nearly 300 per cent of the minimum in two sets, nearly 200 per cent in two sets and over 150 per cent in one set. Evidently some of the pieces obtained good bearing and others in the same set did not, and thus created a series of column actions within the pieces. In these pieces an average of the three pieces must not be taken but rather the maximum in each case, since they are each of the same identical tile specimen. Below are the results of a few specimens:

TILE	RUPTURE STRENGTH OF TILE, LB.	COMPRESSIVE STRENGTH, LB. PER SQ. IN.	
		MAXIMUM	MINIMUM
No. 1	950	9230	3160
No. 2	640	8230	....
No. 3	330	6950	....
No. 4	760	6280	4120
No. 5	400	5080	1730
No. 6	460	3780	2250

From the above tabulation it is seen that the rupture strength of tile No. 4 was more than twice that of tile No. 3 and yet tile No. 3 showed a higher compression. It is also observed that tile No. 4 was about 11 per cent stronger than tile No. 2 in rupture strength and yet tile No. 2 showed nearly 30 per cent greater compressive strength than tile No. 4.

Results and Observations of Rupture Tests:

When the load in the transverse tests was applied at the rate of 0.0625 in. per minute there was no deflection perceptible with a 0.001-in. deflectometer placed under the bottom of the tile central under the load on a 12-in. span. The failures were of three general characters, a split along the longitudinal center line, a diagonal end to end split or a combination of these two, and a transverse split or break across at the middle point.

It was noted that the tile from a particular manufacturer would invariably fail by only one of the three types of failures mentioned. The majority of the weaker tile broke transversely at the center of the tile. However, one manufacturer's tile averaging a high strength had characteristic transverse failures.

The results obtained from the rupture tests were very satisfactory and consistent and the method permitted rechecking with a marked degree of accuracy. It has been found that the increasing of the arch will slightly increase rupture strength. However, many tiles of extremely flat arch were much stronger than others of high arch and the strongest tile tested was an extremely flat arch of average thickness which carried 1400 lb. The element of thickness seems to have a very marked effect upon rupture strength of tile of the same manufacture. A variation of $\frac{1}{16}$ in. affected the strengths at least twenty per cent. Tiles made of mixtures of clay were considerably stronger than the general run made of only one kind of clay. Particularly high strengths were noted in those tiles having mixtures of fire clay and grog. Since different mixtures of clay are used to obtain light and varied colors, it was shown to be unwise to estimate the strength of a tile from its color. Due to the various clay mixtures used in manufacture and the various degrees of burning it is apparent that the color, thickness or height of arch can not be justifiably regulated in considerations of quality or strength.

Tiles of the same manufacturer, color, thickness, shape and apparently every detail when tested on the 12-in. span showed from 10 to 20 per cent greater strength than when tested on the 5-in. span. Because of this apparent inconsistency a great many such comparative tests were made both on Mission type and on Spanish type tile with the same results. There may be an element of bending moment in the longer span which effects a greater resistance than the more direct splitting tendency on the 5-in. span.

The average rupture strength of the hand-made Missions of reliable manufacture was about 450 lb., while the average of the machine-made Missions was about 627 lb. The average of hand-made Missions from three less reliable manufacturers was about 250 lb. All of these averages apply to the 12-in. span.

It was observed that with the tile generally acceptable as well-made, well-burned tile, either hand-made or machine-made, 450 lb. was about the low limit with 1400 lb. as the high limit, and that all of such tile had an absorption in 48 hours in cold water of less than 15 per cent.

It was found that good tiles of the same manufacture, size and color were as strong when tested fully water soaked as when thoroughly dry.

It was found that the medium of transmitting the load had little or no effect upon the results. Identical tile were tested using a solid steel pin horizontal as referred to; a block of 2 by 3-in. Douglas fir on end; and a $\frac{3}{4}$-in. square steel bar having been bent U-shaped with a 2-in. spread between the two ends, providing a two-point bearing which was placed longitudinally and also transversely upon the tiles. No variations in results by using these different methods of transmitting load were apparent.

In formulating this test method for building codes, a difficulty was discovered in that some of the Spanish one-piece tiles were only 12 in. long with a bevel cut at diagonally opposite corners and that the supporting span could not exceed 10 in.; and also that the building code should have only one span designated. A further series of tests was run using a 10-in. span instead of a 12-in. span. Practically no difference was noted in the results except that as before the 10-in. span supported a greater load than the 5-in. span. Therefore the 10-in. span seems most desirable.

CONCLUSIONS

From the data obtained from these experiments and from the results of hundreds of tests which have been made subsequent to the adoption of the rupture test, it is concluded that the rupture of a whole tile when supported on bearings with a concentrated load at the center is the most reliable method thus far developed in determining the quality, strength and probable endurance of a roofing tile, and to this is arbitrarily added a requirement that the tile shall not absorb more than 15 per cent when immersed 48 hours in cold water.

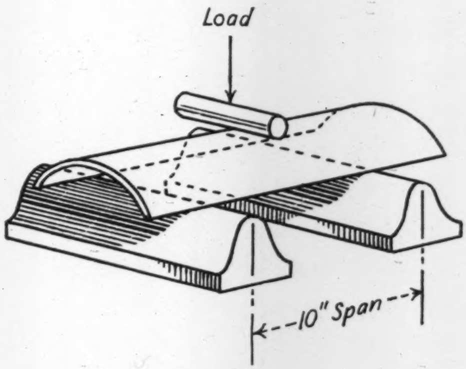


FIG. 2.—Laboratory Set-up for Testing.

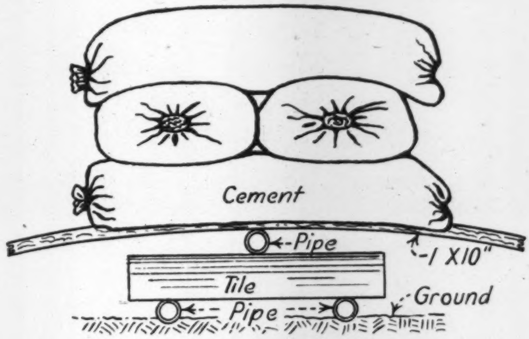


FIG. 3.—Field Set-up for Testing.

This test seems to be the most reliable, economic and simple to perform. It also most nearly duplicates the field condition and is applicable to all variations of curved type tiles.

With a minimum load requirement this method can be used in the field by properly supporting a tile on two pieces of pipe for the span and carefully loading the center of the tile with sacks of cement or sand laid on a board having another piece of pipe thereunder for the contact point. Or, other job methods can be used as are now being used at some of the manufacturing plants consisting of a simple apparatus for applying the minimum load. Illustrations of the laboratory and field test methods are given in Figs. 2 and 3.

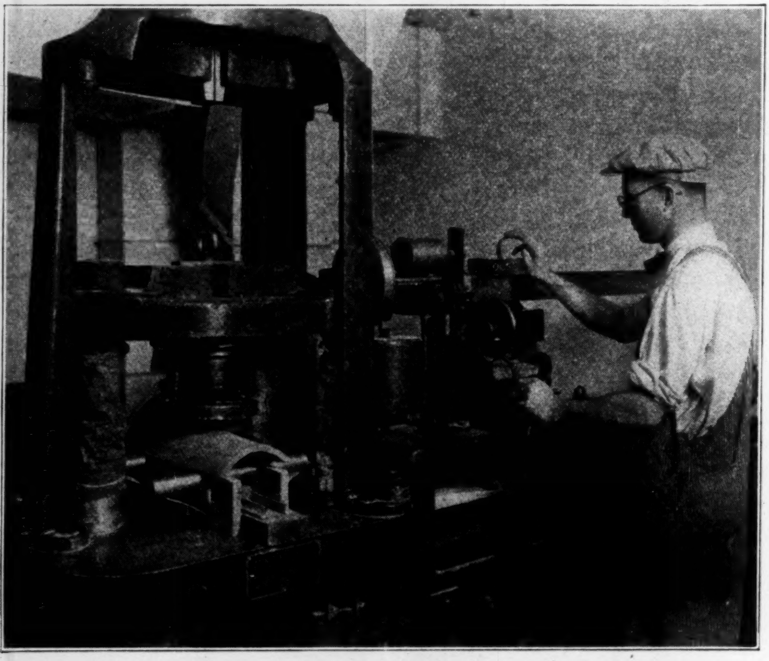


FIG. 4.—Osborne Apparatus Used in Testing Roofing Tile.

SPECIFICATIONS

The Clay Products Institute of California has adopted the following test requirement for roofing tiles as a standard and these requirements have already been incorporated into many building codes in the state:

1. *Absorption.*—Tile used for roof covering shall not absorb more than 15 per cent of its constant dry weight during 48 hours immersion in water.

2. *Strength Test.*—Roofing tile, other than flat pan or flat bottom tile with or without flanges, or flat shingle or flat decorative tile, shall satisfy the following strength requirement: When supported on the turned-down edges at points 5 in. each side of the center of the tile, giving four points of support and a span of 10 in., and loaded with a concentration at the center, the average breaking load per tile, for five representative tile tested, shall be not less than

400 lb., and the breaking load for any individual tile shall be not less than 350 lb.

3. *Soundness.*—Roofing tile shall be free from injurious cracks, and shall ring clear when lightly tapped.

Some cities when incorporating these test requirements into their codes have outlined a method of selection of samples, periodic reports, etc.

REMARKS

A great many tests have been made on flat Italian pan tile and flat shingle type tiles by supporting them horizontally upon four contact points of bearing near the corners by using vertical pieces of $\frac{1}{2}$-in. screw pipe with pipe reducers for bases and spherical knobs for contacts. The pipes were adjusted similar to the leveling screws on a transit. A load was applied at the center point of the tiles. A curious thing observed in these tests was that a tile, say 12 by 14 in., would break laterally leaving a piece about 12 by 7 in. and when this half was similarly tested it showed invariably the same breaking strength as the whole tile. So also did smaller pieces of the second break 7 by 6 in., etc.

The loads on the flat tiles varied widely according to their thickness and composition. One set of about thirty tests averaged 275 lb. breaking load on flat shingles, with a spread from 159 to 399 lb. Another series of shingle tiles had an average of about 350 lb., with a spread from 195 to 560 lb. Another series of Italian pans with 90-deg. flanges averaged about 375 lb., with a spread from 240 to 480 lb. Another series of Italian pans with the flanges turned up about 45 deg. showed an average of about 420 lb. with a spread from 390 to 475 lb.

This institute is programming additional study on roofing tiles in the nature of permeability tests and toughness tests, the latter involving impact or shock tests. Where the former may be of particular value, the latter may be only informative or of comparative interest.

SYMPOSIUM ON ROSIN

INTRODUCTION

BY F. P. VEITCH[1]

Rosin is one of the important raw materials of a number of industries. It is also one of the important products of this country, which is the largest producing country of rosin in the world, producing about 60 to 70 per cent of the total rosin made. But although rosin has been used for many years for a number of purposes, unfortunately, there is not a great deal of reliable data, other than rule-of-thumb data with regard to rosin, and it has been the hope of the Society's Committee D-17 on Naval Stores, under whose auspices this symposium has been arranged, that through this symposium we might be able to get all of this information that is well known to those interested in the use of rosin.

This is the second symposium on this subject, the earlier one having been held in 1926.[2] Since then a good deal of information, it is thought, has been developed by various users, and it is the hope of the committee to bring this information up to date at a symposium of this kind through the presentation of eight papers covering certain specific uses of rosin and through the discussion which these papers will elicit.

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[1] Chemist in Charge, Industrial-Farm Products Division, U. S. Bureau of Chemistry and Soils, Washington, D. C.

[2] Symposium on Rosin, *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 493 (1926).

ROSIN IN THE MANUFACTURE OF ROSIN ESTERS

By Stephen Babcock[1]

In this paper "ester gum," the term used in the industry, refers to the combination of glycerin with rosin.

In the eighteenth century a varnish maker in England secured a patent for the process of treating rosin with lime. This patent did not, however, deter others from using the process, which every varnish maker did without fear of prosecution. This process was later improved upon by adding some glycerin to the kettle. It remained for a German chemist, Doctor Schaal, a century later to apply scientific knowledge and produce by means of a specially designed apparatus, the ester gum as we know it today. He secured a patent for this process and improved upon it from time to time.

About the year 1900, rosin was beginning to lose its standing in the varnish industry, as Congo gum and linseed oil made a very good waterproof varnish. About this time one of the largest varnish concerns in this country secured a license to use the Schaal process, producing the ester gum mainly for their own consumption. It was not, however until the advent of China wood oil (tung oil) in about 1906 that attention was directed again towards rosin and its combinations with glycerin.

The American varnish makers were quicker to appreciate the advantage of the ester - wood oil combination over the Congo - linseed oil than were the English, the Congo - linseed oil taking months to "age" as against weeks for the ester - wood oil varnish. In fact ester - wood oil varnish may be shipped in 24 hours after making.

Up to this time, 1906, ester gum was imported into this country only in limited quantity, but with the coming of wood oil there began to show an increased consumption of the imported ester gum and by 1908 it amounted to about 250,000 lb. In 1914, due to the growing airplane industry, the demand for waterproof varnishes increased and this still further increased the demand for ester gum.

At this time there was no factory making ester gum in this country to supply the rapidly growing demand. The Schaal patents were about to expire, and about two years before, two men conceived the idea of starting a factory to make an ester gum that would not darken on cooking to such an extent as did the German and

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[1] John D. Lewis, Providence, R. I.

English esters. They succeeded after two years' trials and thus was started the first ester gum factory in this country.

By 1924 the consumption of ester gum had reached about 9,000,000 lb., most of this going into enamels and waterproof varnish. In 1926 with the increased interest in lacquers, the production of ester gum mounted to over 12,000,000 lb.

At the start, the lacquer manufacturer, looking on ester gum as "rosin," did not take kindly to it as a gum base, and its popularity was not enchanced when it was found that much of the ester gum being produced in 1925 and 1926 did not cut perfectly in the lacquer solvents. Considerable throwout or sludge would be found in the bottoms of the lacquer storage tanks. This problem was studied by the ester gum manufacturers, and before long most of them overcame the difficulty.

I do not have the figures showing the production of ester gum for 1929, but I believe it is safe to say that the production was double that of five years ago. In this estimate I do not take into account the ester gum that is used as a flux in the manufacture of synthetic gums.

Hoping to receive some suggestions that would be valuable to the rosin producer, to the U. S. Department of Agriculture, and to the ester gum industry, the following questions were sent to the ester gum manufacturers.

Is the melting point of rosin important?
Is the presence of dirt harmful?
What style of package do you prefer, wood or metal?
Do you find that some "pale" rosins make dark ester?
Have you any suggestions to overcome this in the grading?
What is a desirable standard for acid number of the rosin?
Is saponification value of importance?
Do you receive much opaque rosin, if so what effect?
Would you suggest a standard specification for "Pale Ester Gum"?
Can you express an opinion as to the relative merits of gum rosin and wood rosin in the manufacture of ester gum?

The answers were not wholly satisfactory, some doubtless believing that the information they could give was regarded by them as confidential manufacturing information. One manufacturer rather politely corrected me for using the term "ester gum," by replying that while they had made only laboratory runs of "ester gum," they had produced and sold large quantities of "rosin ester."

All the replies to the question about melting point indicated that it is important to have as high a melting point as possible.

The presence of dirt appeared to all, except one, as harmful, and this one reported that while he did not like to receive dirty rosin, that only dirt that included iron forming resinates caused any darkening.

The replies to the question regarding package were evenly divided between wood and metal.

With regard to "pale" rosins sometimes making dark ester, all who replied to this question answered "Yes" except one, but no one offered a suggestion as to how this could be overcome in the grading.

In this connection my observations have been that the pale gum rosins, that is grades WG and WW of low acid number, not only show large losses in esterification, but they produce a very dark ester. It is my belief that such rosins were not "dry"—that they carried considerable oil which should have been distilled off in producing the rosin. This would of course affect the grading, and the ester gum manufacturer would not pay a premium for something he did not receive. If the pale grades, WG and WW, could be graded on heated samples, and the acid number not below 158, it would insure the purchaser the quality he would expect.

Every one replying said that an acid number 160 was desired. With regard to saponification value, the opinions were divided, but no one expressed any opinion as to the figure.

The same was true in the answers to the question regarding iodine number.

With regard to opaque rosins, only one reported receiving any, and he said that it caused foaming.

As to the matter of standard specifications of the finished ester, no one desired to suggest any.

The opinions regarding the relative merits of gum and wood rosin are of interest. There was, however, an apparent lack of desire to comment on this. One varnish manufacturer who operates his own ester department says, "In our opinion, wood rosin is not so good for ester gum as gum rosin. Wood rosin produces a paler ester, but varnishes made from it are more apt to become seedy than varnishes made with ester that has been produced from gum rosin."

Another said, "Gum rosin has this advantage over wood rosin when made into ester, in that it has a higher melting point, and frees itself from the solvents more readily. Wood rosin gives higher yields, is free from dirt and foreign matter, is uniform in acid number and becomes paler on esterification."

[For Discussion on Rosin in Rosin Esters, see page 842.—ED.]

ROSIN IN PAINTS AND VARNISHES

By F. W. Hopkins[1]

In the past, rosin has often been looked upon as a material used by a manufacturer to the detriment of a product as an adulterant or otherwise, the use of which he would not care to frankly discuss. However, it is the abuse of rosin, rather than its use, that has caused it to be discredited, for in many instances rosin, because of its peculiar properties, serves purposes such that it could not be satisfactorily replaced by any other material. Rosin is an important necessity. Without it the industries employing oleo products, for example, would be seriously handicapped not only economically but from the standpoint of development.

Were it not for rosin and its peculiar affinity with tung oil, and the adaptation of that combination commercially, millions of dollars would have been lost every year since 1900 both to the manufacturer of finished products and the consuming industry, in lieu of the important economies which it was possible to effect in production, and in many cases, to increase the durability of the finish.

Without an open mind, the development of highly important synthetic resins, which make for further savings and advancement in both lacquer and varnish finishes, would be greatly retarded if not prevented.

Even the use of rosin in metallic driers has become quite indispensable as the finishing touch, to perfect certain outstanding rosin and oil combinations which would otherwise be impracticable.

In a word, all these developments have dovetailed like the progress of a research problem and without rosin another starting point is highly problematical. The statements made have been in reference to varnish and lacquer only, but the same would be true of other industries.

If anyone is "bootlegging" with rosin, I can understand why he does not care to discuss it openly. But if one is using rosin constructively, he need have no qualms about being frank. Let us not be mistakenly secretive. Frankness in discussing the use of this wonderful gift of nature should lead to greater possibilities for its use.

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[1] Assistant Manager, Technical Department, Murphy Varnish Co., Newark, N. J.

During the past five years, 1924 to 1928 inclusive,[1] the paint and varnish industries have used on an average of 228,182 500-lb. barrels annually or approximately 25 per cent of the rosin consumed by all the industries using rosin.

The use of this rosin may be divided into three classes, varnish, synthetic resins and metallic resinates or driers.

Varnishes:

In the manufacture of varnishes from fossil gums, approximately 10 per cent of the gum content in the kettle is rosin, used as a flux to reduce the melting point, preserve color and assist the compatibility of the gum and oil. Rosin is used in varnishes with tung oil in one of two forms—either natural or in a hardened state. When used natural, the kettle is loaded with rosin and oil and heated to a range of 525 to 575° F. (274 to 301° C.). At about 480° F. (250° C.) metallic salts are added such as oxides, acetates or resinates of lead, cobalt and manganese for drying purposes, and calcium derivatives for neutralizing purposes.

Hardened rosin might be termed a weak resinate, as the rosin is melted and the lime of high calcium content added to the extent of 6 to 8 per cent. Other hardening agents are sometimes used, all depending upon the qualities desired; such as zinc oxide, aluminum hydrate and magnesium carbonate. The same procedure is followed in the manufacture of a varnish with a hardened rosin as with natural rosin, only metallic salts are used in lesser amounts. Inexpensive spar and rubbing varnishes are usually made with rosin or hardened rosin as the gum content.

Gloss oils are, in reality, hardened rosins in solution in mineral spirits or turpentine. Sometimes a small amount of tung oil is used in making a gloss oil which imparts a tougher film and the durability, to an appreciable extent, is lengthened. These are used as blending varnishes or in inexpensive paints. They produce initial high gloss but lower durability.

Undoubtedly, during the early advent of tung oil, some varnish maker was rather pleasantly surprised when he discovered that by throwing a handful or two of rosin into a varnish kettle containing a batch of tung oil varnish which had started to polymerize, that the reaction was quickly checked. Sometimes, tung oil base pigmented materials will react so that the tung oil polymerizes and starts to jell. An 8-lb. cut of rosin in either mineral spirits or turpentine added sparingly will check this.

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[1] Figures compiled from statistics furnished by the U. S. Department of Agriculture.

The high acid content of the rosin is an unique solvent for the tung oil polymer; but the durability of the pigmented material is proportionately reduced by excessive use of such a solution.

Synthetic Resins:

Undoubtedly the largest amount of rosin used by the paint and varnish industry is in the form of ester gum. The rosin is esterfied by the addition of approximately 10 per cent glycerin, usually in a closed kettle, because uniform pressure and vacuum may be maintained, producing paler color, lower acid number and higher softening point. Ester gum makes a tougher and more durable varnish than natural rosin. It is possible to manufacture a false body varnish with ester gum, and for certain processes requiring a high viscosity and thin film, this has useful application. Generally speaking, such a varnish might be called a "bootleg" product. When used with the phenol formaldehyde base resins, rosin converts them into a soluble product with tung and linseed oils. It is used in proportions from 30 per cent to 90 per cent. In the preparation of other synthetic resins, rosin is also used in order to produce better compatibility and solubility. With the exception of certain synthetic resins, ester gum is undoubtedly the only transformed product of rosin which is used to any great extent in lacquers. In lacquers, ester gum imparts a certain viscosity in proportion to the solid content in which it is used, together with an ease of rubbing that is desired by all users of lacquers.

Metallic Resinates:

Resinates are made either by fusing the rosin with metallic salts or by precipitation from a solution. Precipitated resinates are more uniform and reactive because of finer particle size. Generally, the precipitated resinates produce better results, although in some cases the fused products might be used advantageously.

DIFFICULTIES AND THEIR CORRECTIONS

From time to time numerous difficulties have been encountered in using rosin in the above mentioned products. Undoubtedly, up until a few years ago the presence of bark and dirt in rosin caused an unquestionable amount of trouble. Such foreign matter has a tendency to darken varnish products as well as to clog filters and strainers. Rosin in the crystalline form is also very detrimental, not only in the manufacture of varnishes, but particularly in the esterfied product, since ester gum is used not only in varnish but also in lacquer. As an example, some time ago we found that difficulty had been experienced with an ester gum mixing varnish. After aging for a short period of time a seedy condition existed which was directly traced to a crystalline condition of the rosin before the esterfied product was manufactured. A like case was discovered in a lacquer product where the solubility of the ester is very important. In order to be certain that an ester gum manufactured from rosin is not in the crystalline form, the following test may be used: A 10-lb. cut of ester gum is made in ethyl acetate and placed in a refrigerator at 0° F. (−18° C.) or below, for periods of 24 to 48 hours. If the ester gum has not crystallized from the solution in 48 hours, reasonable assumption may be made that the ester is not apt to cause any trouble so far as crystallinity is concerned.

The crystalline form of rosin is changed to the non-crystalline form by following the usual procedure in manufacturing varnish. During the cooking of the varnish, temperatures of 525 to 575° F. (274 to 301° C.) are reached and it is at these temperatures that the change takes place in the rosin.

In the manufacture of ester gum a pre-heat treatment may be made which changes the form of the rosin, although, generally speaking, most rosins darken under such a treatment, but there are some which bleach at these temperatures, and, of course, it is possible to carry out the operation in the presence of an inert gas. Moisture in rosin is likewise detrimental, as it causes excess foaming in both the varnish and ester kettle. If care is taken and the heat raised slowly, this difficulty may be overcome.

All rosin, of course, does not have such detrimental qualities as outlined, but an occasional shipment is received, and care must be taken in the manufacture of the products in which it is used.

SUGGESTED SPECIFICATION

It is estimated that the paint and varnish industry purchases approximately $3,500,000 worth of rosin annually. Nevertheless, I do not believe that careful enough consideration has been given to the purchasing of rosin by specification.

Since rosin cannot be considered a definite chemical composition, as all such natural resins are more or less a combination of compounds, it is rather difficult to write specifications for the purchase of it, as one might purchase certain pigments whose chemical composition is definitely known. Undoubtedly, an ideal rosin for use by the paint and varnish industry might have the following constants, all depending upon where and how it is used.

Package.—Galvanized metal container.

Appearance.—Clean, free from bark, dirt and other foreign material.

Color.—Should conform to the standards set by the U. S. Department of Agriculture, depending upon the material in which it is to be used.

Acid Number.—160 to 170, depending upon the grade, kind and method of manufacture.

Softening or Melting Point.—150 to 180° F. (65 to 82° C.) determined by the Ring-and-Ball Method of the Society; again this depends somewhat upon the grade, kind and method of manufacture.

Loss on Heating.—Maximum percentage at a definite temperature for a certain number of minutes, for example 570° F. (300° C.) for 15 minutes.

Change in Color.—Heated at a definite temperature for a certain period of time, should not darken more than an exact number of grades.

Form.—Non-crystalline—or it shall not show crystalline condition in the finished product after the usual method of procedure has been followed in manufacturing such a product.

Viscosity.—As uniform as possible, depending upon grade, kind and form under present method of manufacture so that it will not cause a variation in the viscosity of the finished product in which it is used.

[For Discussion on Rosin in Paints and Varnishes, see page 843.—ED.]

ROSIN AS A LINOLEUM COMPONENT

By M. K. Bare[1]

In a paper presented before the Society in 1926 by Mr. R. B. Rohrer,[2] the subject of rosin for use in the floor covering industry was very ably covered, and we feel that only a somewhat more detailed account of the amount used, its value, and some of the advances made since that date would be of general interest. The subjects discussed in the former paper were grades of rosin used, effect of dirt, melting point, physical and chemical characteristics, effect of crystalline rosin, and the substances that could replace rosin, and that rosin could replace.

Changes in Rosin Usage and Improvements Since 1926:

During 1928, which is the latest year for which data can be secured, the quantity of rosin used in the linoleum industry reached a total of 29,100,000 lb., which represents an increase of 31 per cent over the 1926 consumption and places the linoleum industry fourth in the usage of rosin, being exceeded only by the paper and paper size, paint and varnish, and soap industries. In 1926, linoleum ranked sixth.

Of the above quantity used in the linoleum industry, about 90 per cent is wood rosin used in linoleum cement and in the cheaper backings and coatings, the remaining 10 per cent being gum rosin used in the preparation of paints where color is a large factor. This latter field has recently been entered by certain manufacturers of decolorized wood rosins. Since the use of gum rosin is almost entirely in making of paints or varnishes, which is covered in another paper, this paper will be confined to a discussion of the part that wood rosin plays in the linoleum industry.

One notable advance which has resulted in the practical elimination of several of the most troublesome defects prevalent at the time Mr. Rohrer presented his paper,[2] is the shipment of rosin in tank cars equipped with steam coils. This does away entirely with the water so frequently met with in barreled rosin, and also prevents introduction of dirt in the form of sticks and splinters from the wooden barrels. The very considerable difference in labor of packaging, handling, bulk in shipping and unpacking of wooden barrels as against loading into tank cars, remelting and pumping through a steam-jacketed line, can be readily seen, as well as the attendant advantages in elimination of foreign material. It has been found that continued heating in the tank cars does not injure the color or produce crystalline rosin, which was one of the doubtful points in installing this handling system.

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[1] **Research Division, Armstrong Cork Co., Lancaster, Pa.**

[2] R. B. Rohrer, "Rosin for the Floor Covering Industry," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 507 (1926).

Tracing Rosin Through the Manufacture of Linoleum:

The only active ingredient in the making of linoleum is the cement or binder, which is made up of oxidized linseed oil, rosin and other resins, such as kauri gum, coumarone resins, etc.

To the best of our knowledge, apparently no change takes place in the organic or inorganic fillers and pigments used in the making of linoleum during mixing and stoving of the goods. Therefore, if it were known what was occurring in the production of the cement, its mixing with the other ingredients and subsequent stoving, we could definitely say just what properties would be desirable in a rosin for linoleum manufacture. Unfortunately, the actual knowledge on all of these steps is very limited, because of the extremely complicated chemical structure of an oxidized oil-resin dispersion.

In the cement-making operation, which is carried out in steam-jacketed kettles, the rosin is used chiefly as a peptizer or solvent for the oxidized linseed oil. There is some relation between acidity of the rosin and this quality of peptizing the oxidized oil, with the high acid value rosins apparently being better in solvent power. A limitation in this respect, however, is the high melting point of the more acidic rosin. As it becomes more nearly pure abietic acid, the melting point naturally rises, in the purest specimens being about 180° C. (355° F.). This compares with wood rosin of melting point about 75° C. (165° F.). Since it is necessary to maintain a large temperature excess over the melting point in the cement kettles and in the intermediate storage tanks in order to keep the rosin sufficiently fluid, this state of fluidity with the highly acid rosins would be dangerously near the flash point, and on adding the cold oil in cement making there would be danger of the entire mass solidifying. Another limitation on these highly acid rosins is their relatively poor alkali resistance when compared to goods in which rosin containing the normal quantity of resenes is present.

At this point it may be stated that in spite of the scores of other acidic materials that have been tested for obtaining a better understanding of this action of peptization of the oxidized oil, no other substance has been found that imparts to the cement the desirable properties of heat sensitivity, satisfactory maturing time, and stability on aging that wood rosin gives. The acidity range of wood rosin has been held so constant by the manufacturers that a complaint on this score is rare. This property, however, is always tested before a lot of rosin is accepted. Color is also determined, because an exceptionally dark rosin might easily cause large losses if made into cement and used in light colored goods.

In the incorporation of the binder with the fillers and colors of a linoleum mix, the rosin in the cement gives the binder the requisite heat sensitiveness to enable it to mix readily under the action of the compounding machines.

After calendering or pressing, the goods are in a soft condition, entirely unsuited to resist the wear and indentation that linoleum is subject to receive. Heating of the goods in large ovens is the next step in the process. This brings about a progressive hardening effect, which is continued until samples have passed standard abrasion and indentation tests. So little is known of this process that it cannot definitely be said that the rosin used plays a controlling or a subsidiary part in this change of the binder on heating. Here the changes occurring in the oil-resin gel are further complicated by the admixture of the colors and fillers of the mix.

The value of rosin in linoleum does not end even when the goods have been matured. A very important function is its stabilizing action on the oil-resin gel, which over long periods, sometimes as much as forty years, enables linoleum to remain as flexible as when first produced. In actual practice, of course, it is necessary only to maintain this condition until the linoleum is laid; but the large factor of safety, in which rosin plays an important part, is of definite value. Here, again, it has been found that many of the materials which have been tried as rosin substitutes are deficient in this stabilizing property.

Conclusions:

It is to be noted from the above outline that an enormous amount of work remains to be done on the action of rosin in linoleum, some of which has been started, but which is not complete enough to be presented in a paper at the present time. Until more data is at hand, no specifications for the ideal rosin can be set, but the following qualities are desirable:

1. Ability to peptize an oxidized oil,
2. Standard acidity, and
3. Light color consistent with price.

In our own case, water, dirt and crystalline rosin have been almost entirely eliminated, but these factors are also important in the production of rosin for linoleum.

Summarizing, wood rosin as now prepared is an excellent cement-making material, combining the advantage of low cost with apparently maximum peptizing effect. Cooperation between the linoleum manufacturer and the rosin producer with the object of obtaining a better understanding of the function of rosin in the manufacture of linoleum should be of mutual benefit.

Acknowledgment.—Acknowledgment is made of the helpful criticism of Mr. Rohrer and Mr. Claxton in the preparation of this paper and to the Armstrong Cork Co. for permission to present it.

[For Discussion on Rosin in Linoleum, see page 845.—ED.]

ROSIN AND ROSIN OIL IN RUBBER AND RECLAIMED RUBBER

By H. A. Winkelmann[1] and E. B. Busenburg[2]

Rosin and rosin oil have been used for many years in rubber compounds and reclaiming. In spite of this fact, no systematic work on rosin or rosin oil has ever been reported and the rubber literature contains but few references. The literature does not differentiate between the available grades of rosin and fails to specify the particular grade which was used. With so little information at hand, it is not surprising that rosin may often have been improperly used, and the experience of such instances has gradually accumulated so that one frequently hears the statement that compounds containing rosin do not age well. While some report unsatisfactory results with rosin or rosin oil there are others who have obtained very good results. Such contradictory reports emphasize the importance of a thorough study of rosin and rosin oil in rubber and reclaimed rubber, which will stress both the advantages and limitations of these materials and consequently make possible a more intelligent choice and use of the different grades.

Since the introduction of rosin, rubber compounds have changed from a rubber-sulfur mix, to a rubber-sulfur-litharge or other inorganic accelerator mix, and finally to those containing various organic accelerators. Rosin and rosin oil should be used with due regard to their effect on factory processing, to their effect on other compounding ingredients and on rate of cure. Rosin is an efficient softener and it is possible that stiffness has often been obtained by cure, rather than by compounding, thus resulting in poor aging due to overcure. Rosin and rosin oil can be used in rubber compounds with satisfactory results if properly compounded. In addition to presenting some original data, the authors have incorporated much valuable information placed at their disposal by a large number of chemists in the rubber industry.

The literature on rosin and rosin oil in rubber compounds consists of a few scattered references which indicate that both materials have been used for a long time. The reclaimed rubber literature, however, contains some valuable references on the early use of both materials.

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[1] Palmer Gas Products Corp., Akron, Ohio.

[2] Philadelphia Rubber Works Co., Akron Division, Akron, Ohio.

H. L. Hall[1] in 1858 heated vulcanized rubber in lime water, water or direct steam. He added rosin either prior to or after the heat treatment. J. H. Cheever[2] in 1860 used the distillation product of rosin for devulcanization. C. McBurney[3] in 1861 treated 100 parts of vulcanized rubber with 40 to 50 parts of rosin oil by allowing the mix to stand for 24 to 75 hours. The product was used in rubber compounds. E. Hunt[4] in 1866 treated vulcanized rubber below 300° F. with rosin. The rubber was recovered by precipitation with wood alcohol, and used for waterproofing. S. M. Allen[5] in 1887 treated fiber containing scrap rubber with equal parts of rosin. S. Kenyon[6] in 1889 dissolved vulcanized rubber in rosin or rosin oil at 240 to 300° F. T. Seehausen[7] in 1899 added 20 per cent rosin oil to 100 parts of vulcanized rubber and devulcanized for 2 hours at a pressure of 45 lb. W. A. Köneman[8] in 1906 used rosin as a softener in a modified acid process of devulcanization. E. L. Rouxeville[9] in 1907 devulcanized with pine resin and purified the rubber by washing with alkali and then with acid. H. B. Cox[10] in 1916 used a solution of rosin in gasoline, naphtha, etc., for devulcanization, and J. F. Johnston[11] (1919) simply used rosin as a softener in the regular alkali process. S. E. Shepard and J. J. Schmidt[12] (1926 and 1929) digested hard rubber with sodium hydroxide and after washing and drying treated it with rosin and China wood oil (tung oil) at 200 to 250° C. (390 to 480° F.). The fused mass was dissolved in a solvent and used as a waterproof coating, paint or varnish.

The United States Department of Commerce in reporting the annual consumption of rosin, does not give any figures for the amount used by the rubber industry. A conservative estimate places the consumption of rosin by the rubber industry at 5,000,000 lb. annually.

Two types of rosin—gum and wood—are used. Each type consists of a number of grades which are classified according to color and impurities. The comparative effect of these grades in rubber compounds or reclaiming has not been previously reported. Gum rosin is graded according to color in thirteen different grades from the darkest which is grade B, to the lightest which is grade X. Grades B, D and E are classed as low commons; grades F, G and H, as high commons; grades I, K and M as mediums and grades N, WG,

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[1] United States Patent No. 20,242 (1858); and No. 22,217 (1858).

[2] English Patent No. 325 (1861).

[3] United States Patent No. 33,094 (1861).

[4] English Patent No. 1,667 (1866).

[5] United States Patent No. 375,436 (1887).

[6] English Patent No. 14,150 (1889).

[7] English Patent No. 7,798 (1899).

[8] United States Patent No. 823,053 (1906).

[9] French Patent No. 375,709 (1907).

[10] United States Patent No. 1,202,760 (1916).

[11] United States Patent No. 1,291,535 (1919).

[12] United States Patent No. 1,583,703 (1926); and No. 1,701,129 (1929).

WW and X as pales. Typical analyses of the various grades of gum rosins are given in Table I. There are seven grades of wood rosin which cover practically the same color range as the gum rosins. grade B wood rosin corresponds to the low commons; grades FF, L (limed) and N wood rosins correspond to the mediums, and grades I, M and commercial abietic acid correspond to the pales. The color of a rosin may not be indicative of its effect in rubber and it may be of greater importance to study the physical and chemical analysis of the rosin. Table II gives analyses of typical wood rosins and indicates what wide variations exist in melting point, acid number, saponification number, etc. These variations may affect the processing properties of the uncured compound as well as those of the cured product. When referring to rosin, it will avoid confusion and misunderstanding to specify the type and grade that is being used.

TABLE I.—PROPERTIES OF GUM ROSINS.

Grade	Melting Point		Acid Number	Unsaponifiable Matter, per cent	Saponification Number	Gasoline Insoluble Matter, per cent	Petroleum Ether Insoluble Matter, per cent	Specific Rotation, deg.	Ash, per cent	Color		
										Lovibond		Standard Cubes
	deg. Cent.	deg. Fahr.								Amber	Red	
B......	86.5	187.7	165.6	7.2	175.2	2.5	4.3	+21.6	0.098	80	210	Less than D
F......	89.5	193.1	162.8	8.5	173.0	1.6	4.6	+8.0	0.046	80	48	E to F
I......	86.5	187.7	166.2	6.4	176.0	1.5	3.4	+30.6	0.025	80	3	I
N......	81.5	178.7	162.7	8.9	176.0	1.1	1.8	+24.0	0.03	77	...	N
WW...	81.5	178.7	162.6	9.8	171.9	0.4	1.2	+30.2	0.033	33	...	WW

TABLE II.—PROPERTIES OF WOOD ROSINS.

Grade	Melting Point		Acid Number	Unsaponifiable Matter, per cent	Saponification Number	Gasoline Insoluble Matter, per cent	Petroleum Ether Insoluble Matter, per cent	Color		
	deg. Cent.	deg. Fahr.							Amber	Red
B.............	85	185	126	11.5	.....	51.5	45.0	Dark	..	....
FF............	78	172	150 to 155	6 to 10	168 to 175	8	7 to 10	Ruby Red	80	75 to 120
I.............	80	175.5	163.4	7.3	171.1	0.06	1.5	Red	..	....
L.............	91	195	133	11.5	147	10	....	Amber Red	..	....
Commercial Abietic Acid......	78	172	80.5	7	174	0.05	0.75	Water White	..	....

There are two kinds of rosin oil—the synthetic or blended type and the distilled. Blended rosin oil is prepared by dissolving 30 to 40 per cent of rosin in mineral oil. Pine oil or kerosine have also been used. The grade of rosin and kind of oil used have a marked effect on the behavior of this type of oil. It has an acid number of about 60 to 65.

Distilled rosin oil is prepared by the distillation of rosin and has an acid number which may run as high as 155. It is, therefore, not at all similar in composition to blended rosin oil and it is unfortunate that both materials are known as rosin oil. Both rosin oils could hardly be expected to give the same results in rubber. The difference in composition and acid number of blended and distilled rosin oil may account for many contradictory opinions regarding the behavior of rosin oil in rubber. At present there is very little distilled rosin oil used in rubber. L. E. Weber[1] in 1926 writing about synthetic or blended rosin oil stated, "Such a mixture should not be used by the rubber manufacturer."

Blended rosin oils having an acid number of 60 to 65 have been used in rubber compounds for many years with as good physical properties, aging and service results as may be obtained with other materials used for the same purpose. The acid number and rosin content of retort and kiln pine tar lie in the same range as those of blended rosin oil. This may be illustrated by the following analyses of some commercial samples:

	ROSIN CONTENT, PER CENT	ACID NUMBER
Blended rosin oil	35	65
Light retort pine tar	31.55	70
Kiln pine tar	36.95	90

The above figures are a useful guide in interchanging softeners where it is desired to keep the rosin content the same. It is interesting to note that it has been common practice to substitute rosin for pine tar on this basis. There are also blended rosin oils on the market containing as high as 80 per cent rosin. If a blended rosin oil having a high acid number is substituted in rubber for any of the above, the cure must be carefully checked. A neutral rosin oil, having an acid number of 8 has been tried out experimentally with good results. This rosin oil lacks the activating power of one with a high acid number, but shows good aging properties.

Rosin is used in rubber compounds to produce softness and tackiness during the manufacturing processes. It acts as an activator of inorganic accelerators and sometimes of organic accelerators. Activation is often inhibited due to the softening effect of the rosin. H. P. Stevens[2] added colophony (rosin) to resin-free rubber and obtained the same vulcanization coefficient as was obtained with the untreated rubber. The activation of rosin during vulcanization is brought out by Stevens in the following table using 7 parts of sulfur on 100 parts of rubber:

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[1] L. E. Weber, "The Chemistry of Rubber Manufacture," p. 230 (1926).

[2] *Koll Zeitung*, Vol. 14, p. 91 (1914).

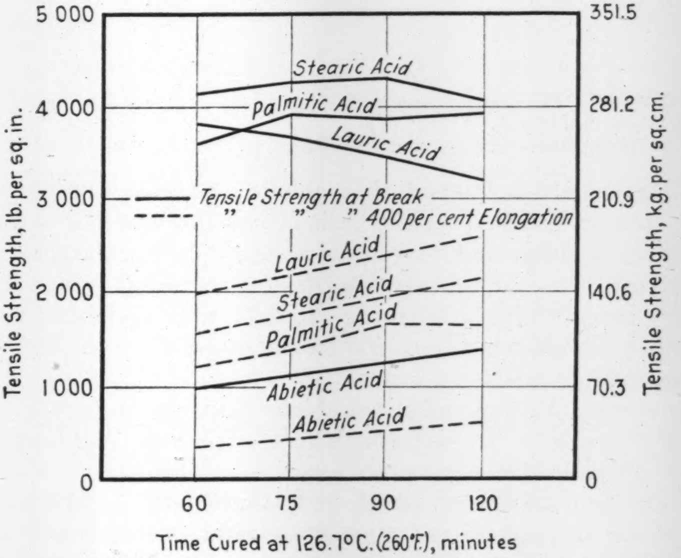

FIG. 1.—Showing Comparison of Acid Softeners Activation of Mercaptobenzothiazole.

Rubber, parts	100
Zinc oxide, parts	5
Carbon black, parts	40
Sulfur, parts	3
Accelerator, parts	0.6
Softener, parts	4

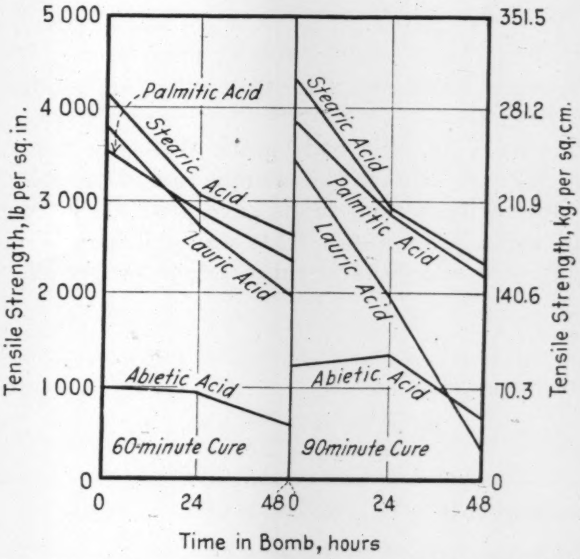

FIG. 2.—Showing Comparison of Acid Softeners, Bierer Bomb Aging.

	MODULUS AT 500 PER CENT ELONGATION, KG. PER SQ. MM.	VULCANIZATION COEFFICIENT
Untreated rubber	0.178	2.86
Resin-free rubber	0.213	2.71
Resin-free rubber + 2.5 per cent Colophony	0.156	2.85

L. B. Sebrell[1] has found that abietic acid when compared with stearic acid on an equal weight basis lowers the modulus and tensile strength of a compound containing mercaptobenzothiazole. When the amount of mercaptobenzothiazole was increased from 1 to 1.75 per cent the modulus and tensile strength were satisfactory. The aging of the latter compound in the oven at 70° C. (160° F.) was the same as obtained with stearic acid.

Since rosin consists mainly of abietic acid, the authors compared a purified sample of the latter with stearic, palmitic and lauric acids for the activation of mercaptobenzothiazole (Fig. 1). Lauric acid speeds the cure more than stearic or palmitic acid. The softening effect of the abietic acid is very much greater than that of the fatty acids, which partially accounts for the slowing up of the cure. Abietic acid is soluble in rubber whereas stearic acid is not, therefore this comparison is not quite fair but it is presented only from the standpoint of activation. The oxygen bomb aging (Fig. 2) is interesting because while the compound containing abietic acid is undercured, the tensile strength has not decreased after 24 hours' bomb aging.

W. W. Vogt[1] compared grades WW, N and E gum rosins in a compound with mercaptobenzothiazole as accelerator. There was no difference between these rosins in their effect on modulus, tensile strength or aging.

According to W. B. Wiegand,[2] grade WG gum rosin has been used commercially for years in the manufacture of tap soles and other products. One of these compounds gave products having excellent physical and aging properties. This was a litharge compound in which the softener-sulfur-litharge ratio were in proper balance:

Rubber	100 parts
Carbon black	80 "
Litharge	13 "
Grade WG gum rosin	4 "
Pine tar	2 "
Sulfur	5 "
	204 "

Cure: 30 minutes at 40 lb. or 15 minutes at 65 lb.

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[1] Private communication, Goodyear Tire and Rubber Co.

[2] Private communication, Binney & Smith Co.

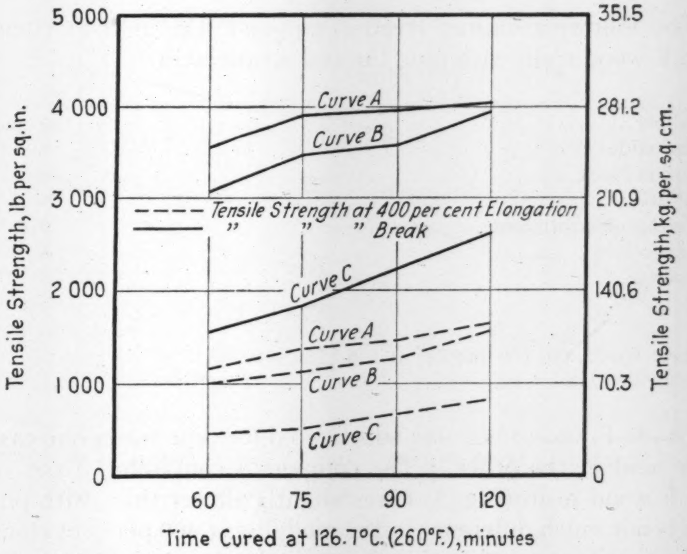

FIG. 3.—Showing Comparison of Softeners in a Tread Recipe Activation of Mercaptobenzothiazole.

	CURVE A	CURVE B	CURVE C
Rubber, parts	100	100	100
Zinc oxide, parts	5	5	5
Carbon black, parts	40	40	40
Sulfur, parts	3	3	3
Accelerator, parts	0.6	0.6	0.6
Stearic acid, parts	4	4	..
Pine tar, parts	3	..	3
Grade F rosin, parts	..	3	4

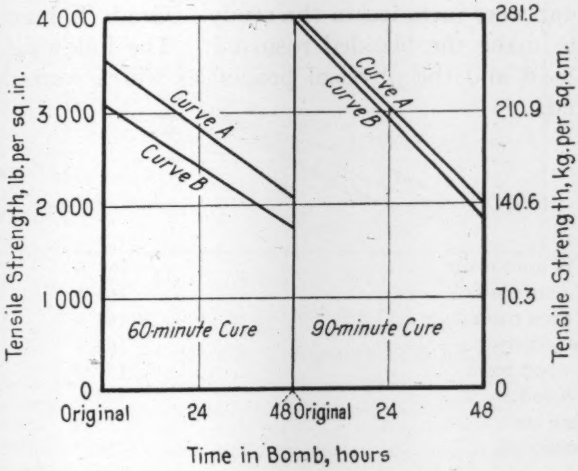

FIG. 4.—Showing Comparison of Softeners in a Tread, Bomb Aging.

The following captax tread compound was used in comparing Grade F wood rosin with pine tar and stearic acid:

Rubber	100	parts
Zinc oxide	5	"
Carbon black	40	"
Sulfur	3	"
Mercaptobenzothiazole	0.6	"
Stearic acid	4	"
Pine tar	3	"
	155.6	"

Cure: 60, 75, 90, 120 minutes at 126.7° C. (260° F.).

Grade F wood rosin was substituted for pine tar in one case, and stearic acid in the other. The compound containing 3 per cent of grade F wood rosin (Fig. 3) cures slightly slower than with pine tar. There is not much difference in the modulus at 400 per cent elongation but the tensile strength at break is a little lower with grade F rosin. The oxygen bomb aging (Fig. 4) of the 60 and 90-minute cures shows no difference between the two compounds. When 4 per cent of grade F rosin was substituted for stearic acid (Fig. 3) the compound was very much softer and the rate of cure was greatly reduced.

A comparison of several grades of gum and wood rosin was made in a pure gum compound, using diphenylguanidine as the accelerator. One-half per cent agerite powder was added to one compound containing grade F wood rosin. A sample of blended rosin oil and medium retort pine tar were included in the study. Grade K gum rosin had been used to make the blended rosin oil. The following grades of rosin were used and the physical properties which were determined are also listed:

	ACID NUMBER	MELTING POINT, RING-AND-BALL METHOD, DEG. FAHR.
Grade WW gum rosin	162.9	176
Grade M gum rosin	164.5	175.1
Grade G gum rosin	167.0	185
Grade I wood rosin	163.1	174.2
Grade F wood rosin	152.3	168.8
Grade B wood rosin	108	180.5
Retort pine tar	73.4	.....
Blended rosin oil	58.7	.....

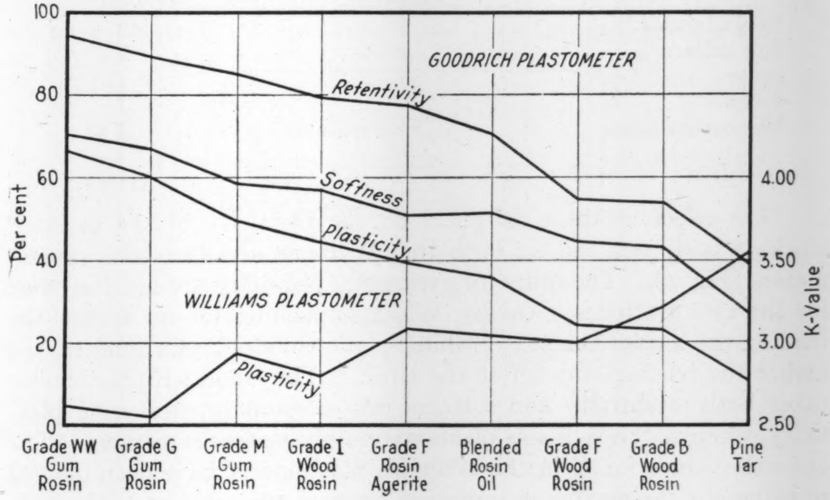

FIG. 5.—Showing Comparison of Softeners.

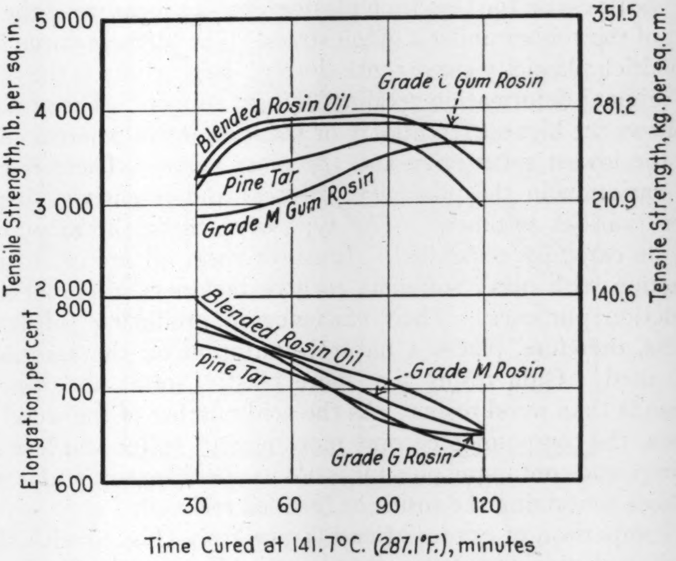

FIG. 6.—Showing Comparison of Softeners.

Smoked sheets, parts	100
Zinc oxide, parts	5
Sulfur, parts	4
Softener, parts	2
Diphenylguanidine, parts	0.75

The above softeners were used in the following compound:

Smoked sheets	100 parts
Zinc oxide	5 "
Sulfur	4 "
Softener	2 "
Diphenylguanidine	0.75 "
	111.75 "

The effect of these softeners on the plasticity of the uncured stocks was determined on both the Williams and Goodrich plastometers (Fig. 5). The units for expressing plasticity are not the same for the two machines. On the Williams plastometer the higher the reading the harder the stock, while on the Goodrich plastometer, the higher the reading, the softer the stock. The Goodrich plastometer takes both retentivity and softness into account in measuring plasticity, whereas the Williams plastometer only measures softness. The ordinate values for K in the Williams plastometer have been plotted to bring out the maximum variation between the samples. The Williams and Goodrich plastometers show that grades WW and G gum rosin give the most plastic stock, while pine tar gives the least plastic stock. Softness on the Goodrich plastometer is a measure of the deformation of the rubber under a given stress. The softness curve follows the Goodrich plasticity curve quite closely. Retentivity is the percentage of original deformation retained by the rubber. The grade WW rosin shows the highest retentivity or the least nerve whereas pine tar shows the lowest retentivity and the most nerve. There is considerable variation in the plasticity, softness and retentivity imparted by these various softeners. The type of rosin or the amount used should be carefully controlled. Rosin or rosin oil are often used in conjunction with other softeners to give tackiness for processing or construction purposes. Their efficiency in producing softness and tackiness, therefore, places a natural limitation on the amount that can be used. Gum rosins give more plastic, softer and less nervy compounds than wood rosins. As the acid number of the wood rosins increases, the compounds become more plastic, softer and less nervy. The compound containing pine tar is not as plastic or soft and is nervier than those containing the rosins or blended rosin oil.

A comparison of grades M and G gum rosin (Fig. 6) with blended rosin oil and pine tar shows that grade M rosin retards the cure. grade G gum rosin and blended rosin oil give higher tensile strength than pine tar. Since the grade WW rosin tensile strength curve would lie midway between grades M and G rosin, it is not shown on the curve. There is very little difference between the softeners in percentage elongation. Oxygen bomb aging (Fig. 7) shows the best results as regards tensile strength for pine tar and poorest for the

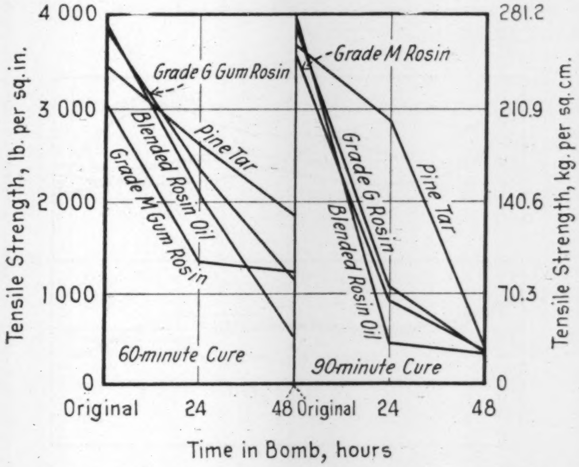

FIG. 7.—Showing Comparison of Softeners in Oxygen Bomb.

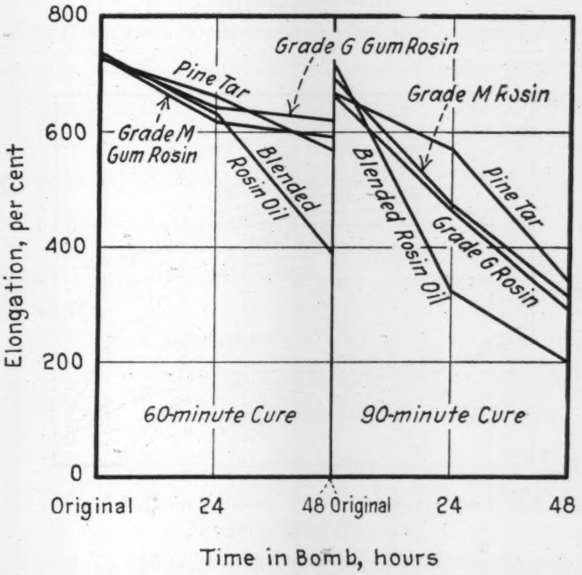

FIG. 8.—Showing Comparison of Softeners in Oxygen Bomb.

blended rosin oil in the 60-minute cure, there is no difference in the 90-minute cure. The decrease in elongation (Fig. 8) of the blended rosin oil is greatest in both 60 and 90-minute cures on bomb aging. There is very little difference between grades M and G gum rosin or pine tar in the decrease in elongation. In view of the plasticity measurements shown in Fig. 5, one might expect a greater difference on aging because of the higher degree of disaggregation of the compounds containing rosin.

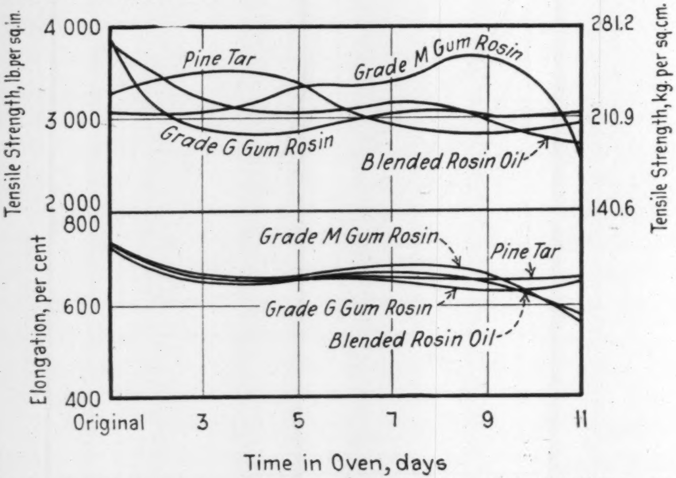

FIG. 9.—Showing Comparison of Softeners in Oven at 70° C. (158° F.), 60-Minute Cure.

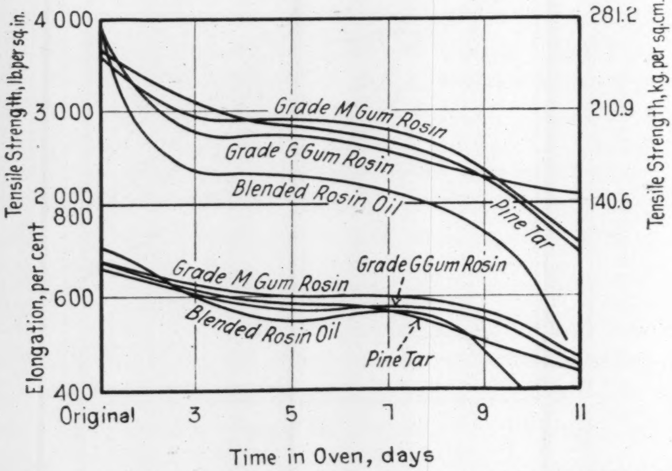

FIG. 10.—Showing Comparison of Softeners in Oven at 70° C. (158° F.), 90-Minute Cure.

Oven aging of the 60-minute cure at 70° C. (158° F.) for 11 days shows very little difference in tensile strength or elongation between grades M and G gum rosin, pine tar or blended rosin oil (Figs. 9 and 10). In the 90-minute cure (Fig. 10) the grade G rosin shows the least

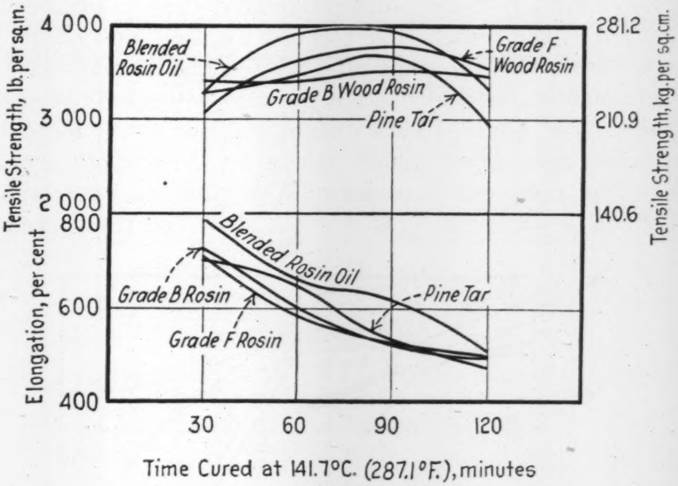

FIG. 11.—Showing Comparison of Softeners.

Smoked sheets, parts	100
Zinc oxide, parts	5
Sulfur, parts	4
Softener, parts	2
Diphenylguanidine, parts	0.75

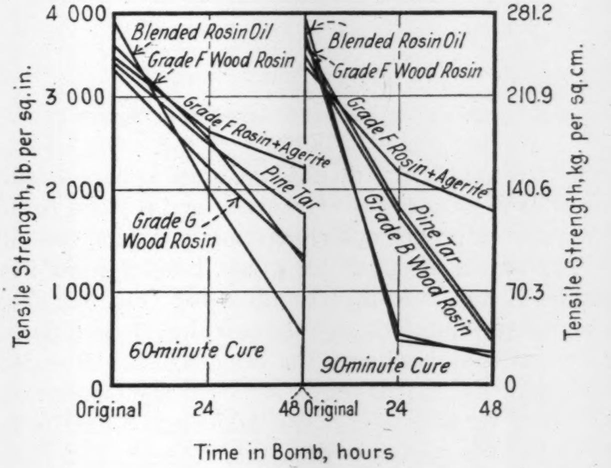

FIG. 12.—Showing Comparison of Softeners in Oxygen Bomb.

and blended rosin oil the greatest decrease in tensile strength. Except for blended rosin oil, which drops off greatly, there is little difference in elongation. The reason that blended rosin oil ages poorly in the 90-minute cure is that the compound has reached its maximum tensile strength in 60 minutes, which is not the case with grade M gum rosin or pine tar. The grade G gum rosin is superior to the blended rosin oil considering rate of cure, tensile strength and aging of the two compounds. The aging curve of grade WW gum rosin corresponds to that of grade G gum rosin so that is not shown on the curves.

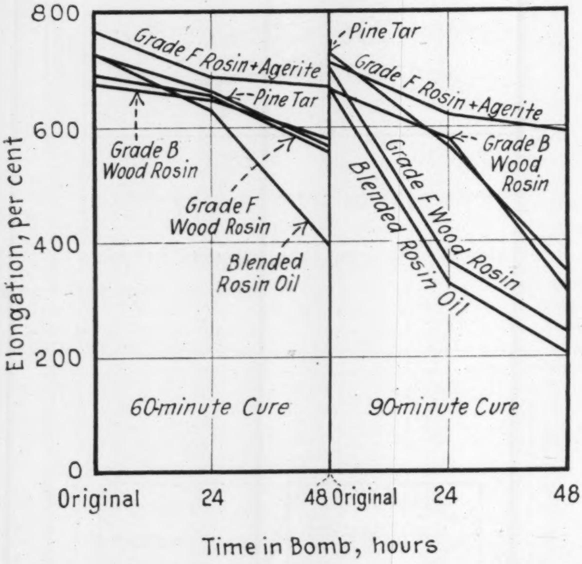

FIG. 13.—Showing Comparison of Softeners in Oxygen Bomb.

The wood rosins (Fig. 11) do not give quite as high tensile strength as grades G or WW gum rosin. Grades F and B wood rosin compare favorably in tensile strength and elongation with pine tar and blended rosin oil. The tensile strength for grade I wood rosin lies midway between grades B and F rosin. Bomb aging (Fig. 12) shows better results with pine tar on the 60-minute cure, but little difference in the 90-minute cure as compared with the wood rosins. Blended rosin oil shows poorer aging as regards tensile strength and elongation (Fig. 13) than wood rosins or pine tar. The addition of agerite powder to grade F wood rosin improves both tensile strength and elongation on bomb aging. There is no appreciable difference in the effect of gum or wood rosins on aging. There is also no practical difference in modulus or reinforcing effect. Oven aging of the 60-minute cure at 70° C. (158° F.) for 11 days shows that grade B wood rosin holds up slightly better in tensile strength and elongation than grade F wood rosin (Figs. 14 and 15). The addition of 0.5 of agerite powder improves the aging of grade F wood rosin. In the 90-minute cure grade B wood rosin gives better aging than pine tar which in turn is better

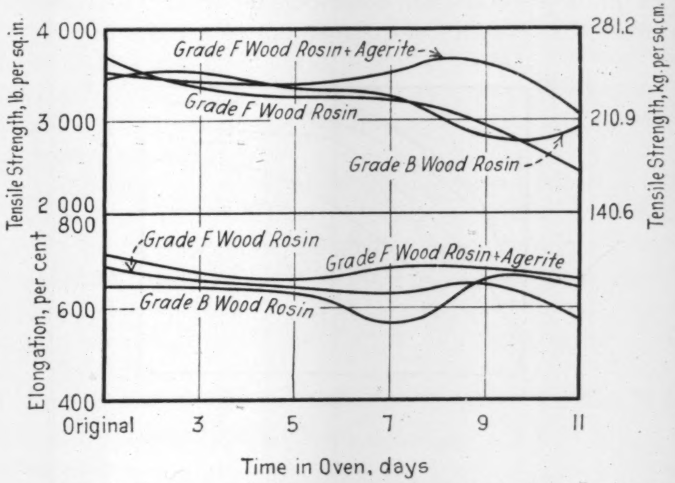

FIG. 14.—Showing Comparison of Softeners in Oven at 70° C. (158° F.), 60-Minute Cure.

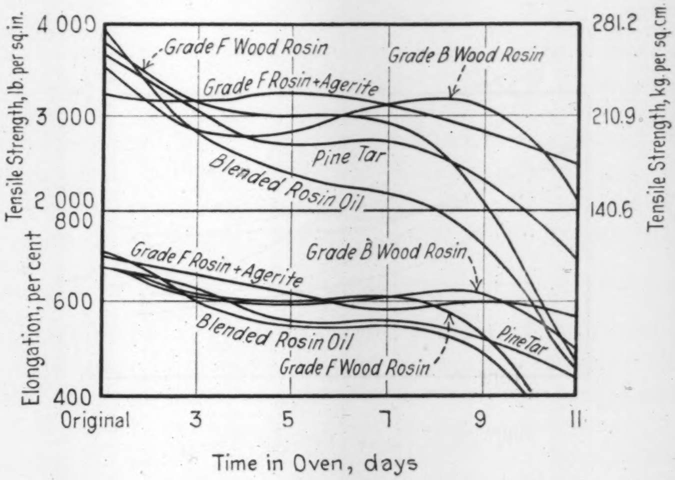

FIG. 15.—Showing Comparison of Softeners in Oven at 70° C. (158° F.), 90-Minute Cure.

than grade F wood rosin or blended rosin oil. The addition of agerite powder again improves the aging of grade F wood rosin. The aging curves for grade I wood rosin correspond so closely to those of grade B wood rosin that they are not shown on the graphs.

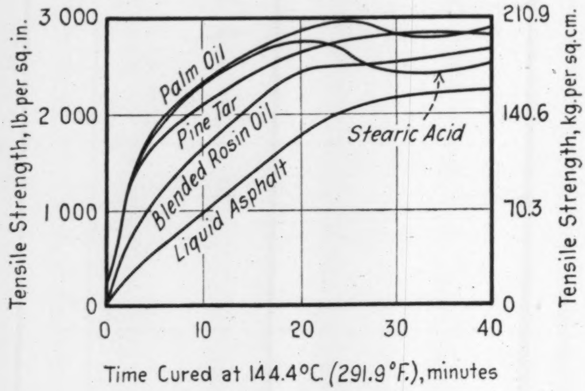

FIG. 16.—Showing Comparison of Softeners.

Blankets, parts	50
Zinc oxide, parts	60
Sulfur, parts	2
Coll. Litharge, parts	10
Softener, parts	5

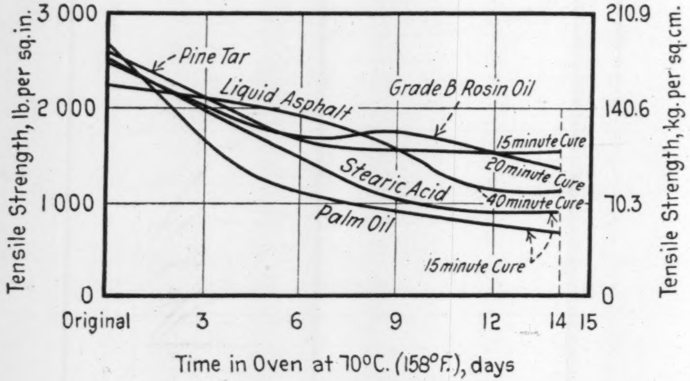

FIG. 17.—Showing Comparison of Softeners, Oven Aging.

There is very little difference in oven aging between the gum and wood rosins in the 60-minute cures. In the 90-minute cures there is no difference on aging between the grades G and WW gum rosins and B and I wood rosins. Grade M gum rosin and grade F wood rosin do not age as well as the other rosins, with the latter giving the poorest results. These results show how important it is to judge processing and aging of two compounds independently. The grade G gum rosin and grade B wood rosin give the same relative aging in the oxygen bomb and oven and yet the grade G gum rosin gave one of the softest and least nervy uncured stocks, whereas the grade B wood rosin gave one of the hardest and nerviest uncured stocks. The physical properties of the two uncured stocks are such that they could not be processed alike.

The activation of blended rosin oil compared with pine tar, stearic acid, palm oil and asphalt in a litharge compound is shown in Fig. 16. The blended rosin oil gives higher tensile strength than liquid asphalt but not as high as pine tar, palm oil or stearic acid. Oven aging at 70° C. (158° F.) (Fig. 17) of the optimum cure of each compound shows that the blended rosin oil compares favorably with the other materials.

A number of years ago, A. H. Nellon[1] tried out a series of blended rosin oils in the following compound:

Smoked sheets	50 parts
Brown crepe	42 "
Sulfur	4.5 "
Zinc oxide	2.5 "
Quinoidine	1 "
	100 "

Three parts of various blended rosin oils were added to 100 parts of the above compound. The tensile strength, elongation, modulus and stress-strain compared favorably with the control and a number of other softeners. Observation of the cures extending over several years showed satisfactory natural aging as compared with other materials.

USE OF ROSIN

Rosin may be used in light colored compounds; it does not stain, and is odorless. It finds its greatest application in cements, friction tape and frictions. It is used to increase tackiness and improve processing of rubber compounds. Rosin is used in vulcanizing and nonvulcanizing cements. A vulcanizing cement in which rosin is used to give activation and tackiness is the following:

Rubber	48 parts
Litharge	18 "
Sulfur	2 "
Grade WW gum rosin	1.5 "
	69.5 "

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[1] A. H. Nellon, private communication, Lee Tire and Rubber Co.

A large outlet of the non-vulcanizing cement is in the leather and leather shoe industry. Grade WW gum rosin, due to its pale color, is used in shoe laying cement and for joining leather to leather, felt or fiber. Twenty-five to 50 per cent of rosin based on the weight of the rubber is used. Rosin is peculiarly adapted for use in these cements because it is soluble in both the rubber and the dispersing medium, gasoline or benzol.

Two special wood rosins having melting points of 195 and 112° C. (383 and 233° F.) with acid numbers of 133 and 98, respectively, have found special application in hard rubber.

Rosin oil is used to soften compounds and improve processing. Synthetic rosin oil was used for years in friction compounds before pine tar was used in any volume. Synthetic rosin oil softens and reduces the nerve of a compound.

RECLAIMED RUBBER

Rosin and rosin oil have been used in the manufacture of reclaimed rubber by the acid, alkali and heater processes for many years. They have been used in the devulcanization of all types of scrap rubber such as whole tire, inner tube, solid tire, airbag, hose, etc. Due to freedom from staining, rosin and rosin oil find application in red and gray inner tube reclaims. The absence of odor is also an advantage in treating all types of scrap rubber. Reclaimed rubber containing rosin has therefore been used in the manufacture of a large variety of rubber products such as tires, inner tubes, belting, hose of all kinds, tubing, insulated wire, auto topping, boots and shoes, heels, etc. In some products larger amounts of reclaimed rubber have been used. The products have had to meet a variety of tests in service such as heat, steam, fatigue, flexing, sunlight, etc. The presence of rosin or rosin oil on the basis of comparative tests has not been detrimental.

Rosin or blended rosin oil may be added to reclaimed rubber prior to or after devulcanization. Rosin and rosin oil must be used on their own merits in reclaim products developed around them for certain purposes. It is impossible to simply substitute one material for another. For example, if rosin is used in place of pine tar a slightly firmer reclaimed rubber is obtained which necessitates further changes in the devulcanizing process to produce a reclaimed rubber of the consistency obtained with pine tar. Rosin improves the physical properties and working properties of a reclaimed rubber. When adding rosin after devulcanization, it greatly facilitates the milling of the rubber. For this purpose a high melting point rosin without excessive tackiness is preferred.

Rosin or rosin oil used in the alkali process of devulcanization results in the formation of a soap. Some of this soap remains in the rubber giving a firmer reclaimed rubber which cures with a higher tensile strength and modulus. The presence of the soap will also have a different effect when the reclaim is used in a rubber compound than when rosin as such is added to the compound or when an acid reclaim containing rosin is used. All of these factors must be borne in mind in judging the effect of rosin in rubber and reclaimed rubber. The alkali reclaim containing some rosin soap will increase the rate of cure and the modulus of the rubber compound.

Acid reclaims have been devulcanized for years with rosin. Both gum and wood rosins have been used, with practically no difference in results. These reclaims have also been used in the manufacture of a large variety of rubber products.

Heater reclaims, that is, devulcanized in open steam, have been prepared with rosin and rosin oils. These age as well as though pine tar or any other softener had been used, and have been successfully used in all types of rubber goods.

AQUEOUS DISPERSIONS OF RUBBER COMPOUNDS

Aqueous dispersions of crude and reclaimed rubber have been made with sodium resinate and with rosin or rosin oil and alkali. Patents covering the use of rosin or rosin oil for this purpose have been granted to H. L. Trumbull and J. B. Dickson,[1], T. G. Richards and G. P. F. Smith,[2] H. E. Cude,[3] R. P. Rose,[4] W. B. Pratt,[5] J. H. Reel and H. E. Cude.[6]

Alkali rosin soaps are well adapted for use as dispersing agents in preparing aqueous dispersions of rubber compounds. The soap decreases the interfacial tension and results in the formation of small particles of rubber which are surrounded by the protective colloid. The molecules of soap tend to orient in the interface so that the metallic end, or polar group, is in the water while the hydrocarbon chain, or non-polar group is in the rubber. The solubility of the hydrocarbon chain in rubber and of the metallic portion in water is peculiarly favorable to adsorption at the interface and consequent lowering of the interfacial tension. Rosin speeds the dispersion of rubber compounds in water by imparting tackiness to the compound during the early stages of adding water to the rubber. Oleic and stearic acid produce dispersions more slowly than rosin because they do not impart tackiness to rubber and the non-polar group is not as soluble in the rubber as is true for rosin. M. C. Teague[1] increases the tackiness of water suspensions of rubber compounds by addition of ammonium resinate or ammonium compounds of rosin.

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[1] United States Patent No. 1,513,139 (1924); and No. 1,668,879 (1928).

[2] United States Patent No. 1,671,316 (1928).

[3] United States Patent No. 1,680,862 (1928).

[4] United States Patent No. 1,680,915 (1928).

[5] United States Patent No. 1,732,027 (1929); and No. 1,755,890 (1930).

[6] United States Patent No. 1,735,547 (1929).

Aqueous dispersions of rubber compounds with rosin as the dispersing agent are being used for a variety of purposes. The application of dispersions in the rubber and allied industries has been frequently discussed and need not be repeated here.[2] Aqueous dispersions of reclaimed rubber are proving to be valuable as a compounding ingredient in the manufacture of products from natural latex. The manufacturer of products from latex can use the same materials employed in ordinary rubber manufacture. The presence of the dispersing agent or rosin soap in the product necessitates careful adjustment of the compound for cure and aging. The proportion of rosin soap speeds the rate of cure and increases the modulus. The compound may also cure harder unless changes are made.

SUMMARY

1. Rosin and rosin oil may be used in rubber with satisfactory results.
2. Rosin and rosin oil may be used in the manufacture of various types of reclaimed rubber for use in rubber products.
3. Gum rosins give more plastic, softer and less nervy compounds than wood rosin.
4. The higher the acid number of wood rosin the more plastic and less nervy the compound.
5. Pine tar gives less plastic, harder and more nervy compounds than blended rosin oil or the rosins.
6. There is very little difference in tensile strength or modulus between gum or wood rosins, blended rosin oil or pine tar.
7. Rosins compare favorably with other materials on aging.
8. Rosin finds wide application in curing and non-curing cements.
9. Rosin may be used with satisfactory results in aqueous dispersion of rubber compounds.

CONCLUSION

Rosin or abietic acid is the cheapest available organic acid of high molecular weight. A complete study of the comparative effect of the various gum and wood rosins on plasticity and other uncured properties of rubber compounds would be of value with reference to tubing, calendering and assembling operations. Their effect in cured rubber under various conditions, namely, oven and oxygen bomb aging, sunlight aging, flexing and compression would definitely stress advantages or limitations of these materials. A careful study of manufacturing methods coordinated with an evaluation of their effect in rubber products would undoubtedly lead to standardized products which would prove to be of value to the rubber industry. An investigation on the choice of rosin and solvent to be used in the preparation of blended rosin oil showing their effect in rubber should be made. A study of the derivatives of abietic acid, such as esters, salts, etc., would bring out some interesting data on products that have not been used. The development of hydrogenated abietic acid or rosin would be welcomed by both rubber and allied industries.

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[1] United States Patent No. 1,746,875 (1930).

[2] H. L. Trumbull, "Colloid Symposium Monograph," p. 215 (1928). See also H. A. Winkelmann, *India Rubber World*, Vol. 78, No. 4, p. 53 (1929), for other references.

It is hoped that research on rosin in rubber may be stimulated as a result of this paper and that much new data will be contributed to the literature.

Acknowledgment.—The authors wish to express their appreciation to the following who have very kindly furnished valuable information which has been incorporated in this paper: A. H. Nellon, L. B. Sebrell, G. P. F. Smith, W. W. Vogt, W. B. Wiegand, and W. N. Jones.

[For Discussion on Rosine in Rubber, see page 848.—ED.]

ROSIN IN CABLE IMPREGNATING COMPOUNDS

By J. P. Millwood[1]

In the construction of electric light and power cables, narrow strips of thin paper, specially made for this purpose, are wound helically about a copper conductor in sufficient number of layers to provide the required thickness of insulation. When the paper covering has been applied, in the case of a single conductor, drying follows directly; in the case of a multiple cable, each of the conductors is separately covered, then assembled and belted, if required, by surrounding with additional wrappings of paper, before the drying operation is begun. Under carefully regulated temperature and vacuum, the moisture is removed as completely as possible, after which impregnation is effected by immersion in tanks containing the saturating compound, kept under suitable temperature and pressure. Without undue exposure, a closely fitting lead sheath is extruded over the impregnated paper, to retain the insulating compound and to protect it from the elements and from outside injury.

At this stage and during the service life of the cable it is important that all parts inside the lead sheath be kept as free from moisture and as filled with saturant as possible. Before shipment, the cable undergoes a thorough inspection, the ends are carefully sealed and the cable leaves the factory on a reel, protected by lagging to save it from damage until it is drawn into the duct of the underground system.

It is only within the last few years that it has really been appreciated how serious and permanent injury may occur to a cable as a result of changes in the volumetric dimensions of the sheath, brought about by carelessly winding on or taking off the reel, by exposure to even moderate fluctuations in temperature and in fact to many conditions encountered in manufacture, in installation and in operation.

From the start of the industry, the saturants or compounds used to impregnate the paper insulation of lead-sheathed electric light and power cables have, with but few exceptions, contained either rosin or rosin oil and sometimes both. These saturating compounds usually consist of solutions of the resinous materials in some of the more or less refined oily or greasy mixtures of hydrocarbons obtained from petroleum. However, there are many cases where rosin is not an ingredient, and then the saturant may be simply any one of the different petroleum products available, from a low-cold-test lubricating oil to the semi-solid, jelly-like grease, known as petrolatum.

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[1] Chief Chemist, The Okonite Co., Passaic, N. J.

Without entering into details as to the reasons which influence the cable manufacturer in the selection of a particular type of saturant, rosin has been used to improve the consistency and tack of the compound, so that it will remain put, to secure more complete and lasting impregnation of the paper and better retention of the saturant during manufacturing processes, to offset the tendency to bleed when ends are cut for splicing, to prevent migration of compound when cable is laid on an incline, to avoid excessive pressures at low points, to lessen the likelihood of formation of objectionable voids, to diminish the susceptibility to ionization trouble, etc.

On the other hand, for more than a dozen years the rosin in cables containing it has been under suspicion as responsible for some of the electrical shortcomings which have interfered with the economic, efficient and uninterrupted operation of some of the underground systems in service during that period. Due to low dielectric strength and high dielectric loss, the operating voltage and permissible current loading of some of these installations was limited and breakdowns frequently occurred in attempting to meet the ever growing demands for larger and larger kva. capacity per cable in order to keep up with the increased demand for electrical energy. These cables heated up when loaded and the dielectric loss increasing with rise of temperature, became progressive owing to the inability of the underground conduit to radiate the accumulating heat. Naturally heat expands the compound causing internal pressure, which may stretch the lead sheath, but if cable is taken out of service or otherwise allowed to cool off, the compound will contract and the sheath may not return to its original dimensions, owing to the lack of elasticity of lead. As a result, cavities or voids will occur and likely be left in the insulation, to become focal points of weakness where ionization trouble starts.

In the expectation of being able to remove thereby some of these undesirable characteristics, reduction in rosin content or omitting the rosin altogether has been strongly advocated, so even a decade ago some of the American manufacturers began to change over to petrolatum alone or with little rosin, only to experience trouble in other directions—that from ionization being probably the most serious. During the last few years there is a tendency for manufacturers to return to rosin, as it has become increasingly evident that petrolatum-impregnated cables are no more immune from trouble than those filled with the old type rosin compounds. On an average, petrolatum cables in service show equally high dielectric loss and greater tendency to ionize. Rosin when blended with petrolatum or the oils used many years ago showed a large increase in dielectric loss and power facto with temperature. Due to improvements in the refining of the oil, in the factory processing of the rosin and in the methods for impregnating cables, there has been a great reduction in dielectric loss and power factor, so that today, rosin-saturated cables are not far different from those with unblended oil. At the same time the dielectric strength has increased over values obtained in the past.

It seems to be practically impossible to exclude gas from cables. All the common saturants contain some dissolved gases, but it is only in the gaseous state, after coming out of solution or as enclosed air, that any gas present inside the sheath can cause injury by ionization. Gases are reasonably good insulators so long as they are not overstressed, when they break down, ionization occurs and they become conductors. Though the ionization voltage varies with the nature of the gas, the lower the pressure, the lower the voltage required to ionize or cause corona. Furthermore, it is known that for the same total void volume, large voids breakdown more readily than well-dispersed small voids, so many small voids are preferable to fewer large voids. From a study of different saturants it appears that the addition of rosin to most saturants seems to favor the formation of a multiple of small voids rather than a fewer number of larger voids.

It is likely that a majority of cable manufacturers still prefer "gum" to "wood" rosin, while at the same time they follow with interest the progress made in the purification of wood rosin and the preparation from it of commercial abietic acid. Rosin oil in cable saturants is not used as much as heretofore, though in the last few years almost water-white specimens have been available and represented to possess desirable electrical properties.

Apparently none of the customary chemical or physical constants leads to a classification of rosins into an order similar to the grades now recognized and based on the color of cubes; nevertheless much can be learned as to the suitability of rosin for cable saturants from a carefully conducted laboratory examination of a really representative sample. For instance, it has been shown by Veitch and Sterling,[1] by Shaw and Sebrell,[2] and by others that the chemical and physical characteristics of rosin change considerably on exposure to air and, as a result of oxidation, the acid number and the iodine number noticeably decrease, while an increase takes place in the saponification number, the matter insoluble in petroleum ether, the melting point and some of the other so-called constants. Also it has been shown that ordinary commercial rosin contains free abietic acid rather than abietic anhydride; that abietic acid readily oxidizes and on heating the oxidized product evolves water forming oxyabietic anhydride; that in the absence of oxygen abietic acid does not evolve water; and that insolubility in petroleum ether is a direct measure of the extent to which the rosin has become oxidized.

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[1] Veitch and Sterling, *Industrial and Engineering Chemistry*, Vol. 15, p. 576 (1923).

[2] Shaw and Sebrell, *Industrial and Engineering Chemistry*, Vol. 18, p. 612 (1926).

As it is important from an electrical standpoint that a cable be as free as possible from moisture or materials which may liberate water, it is obvious that rosin for cable impregnating compounds should be as dry and unoxidized as possible. The desirability of freedom from abnormally insoluble rosin, sand, visible dirt and extraneous matter of any kind is equally evident and, though all may not agree that freedom from turpentine or other associated volatile substances is also of importance, there are some who claim that electrically the compound is better in the absence of such volatile substances. Of course, under present conditions, rosin after it reaches the cable plant has to be subjected to treatment in vacuum kettles, filter presses and other special equipment in order to safeguard it from oxidation, to remove so far as possible undesirable impurities and to adapt it for use in cable saturants.

Anticipating a question, likely to be asked by a producer, as to what particular properties are most desirable in rosin for cable compounds, it is as well to admit it is by no means easy to give a satisfactory answer, as each user may have a different reason for his preference for the special grade he favors; however, undoubtedly most users will agree that there is room for improvement in the matter of greater constancy or lesser variation, both physically and chemically, in the rosin now commercially available under the same classification.

Because of the fact that the producer of rosin is only obliged to meet a color standard in the grading of his product, little or no control is maintained over the other factors which make the rosin more or less desirable as having the special characteristics sought by the user. So long as this grading persists as the sole test, there is little prospect of the consumer obtaining a rosin to meet any specified chemical or physical requirement.

In this connection it may be apropos to ask the producer, in the event of a user wishing a rosin, for example, of high acid number, high iodine number, low percentage of matter insoluble in petroleum ether or conforming to some other requirement in an effort to secure the rosin which experience or theory may indicate as most desirable: are the prospects of his being able to obtain such rosin any better now than they were when the last symposium was held in 1926?[1]

[For Discussion on Rosin in Cable Compounds, see page 849.—ED.]

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[1] Symposium on Rosin, *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 493 (1926).

THE USE OF ROSIN IN INSECTICIDES AND DISINFECTANTS

By R. C. Roark[1]

Rosin is an important ingredient of many of our most essential insecticides. For example, rosin is used in making sticky fly paper and adhesives for banding trees, and in the form of rosin soap it is used in arsenical cattle dips, to emulsify oils in water, and as a "wetter" and spreader for nicotine and other insecticides. Mixtures of fish oil soap and rosin soap are especially effective for these purposes. Rosin soap is also a constitutent of pine-oil disinfectants and coal-tar disinfectants.

Use of Rosin in Sticky Fly Papers

Many formulas for sticky fly paper have been proposed and rosin is an ingredient of most of these. Some of these formulas are as follows:

1. Rosin, 6 avoirdupois ounces; lard oil, 2 fluid ounces; balsam of fir, 1 avoirdupois ounce. The rosin is melted upon a water bath, and the other ingredients are added. The mixture should be spread upon ordinary printing paper which has been previously sized by applying a coating of a thin solution of glue. The paper is coated with the sticky compound while warm by means of a brush. The proportion of rosin must be varied to suit the changes in temperature.
2. Rosin, 150 parts; linseed oil, 50 parts; and honey, 18 parts. The rosin and oil are melted together, and the honey is stirred in.
3. Rapeseed oil, 70 parts; rosin, 30 parts; mix and melt together.
4. Rosin, 60 parts; linseed oil, 38 parts; yellow wax, 2 parts.
5. Rosin, 10 parts; turpentine, 5 parts; rapeseed oil, 5 parts; honey, 1 part.
6. Rosin 2 parts; castor oil, 1 part.
7. Rosin, 8 parts; Venice turpentine, 2 parts; castor oil, 2 parts.

The material used in making sticky fly paper is also spread upon the trunks of trees to keep caterpillars from reaching the foilage. Another composition containing rosin which has been successfully used on a large scale both in Europe and in this country for banding trees is made from the following ingredients: (1) a high boiling neutral coal-tar oil having a density of about 1.15 at 20° C., (2) a soft coal-tar pitch, (3) rosin oil of the grade known as first run "kidney" oil, (4) ordinary commercial quick lime. This mixture contains about 35 per cent of rosin oil.

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[1] Chief, Insecticide Division, Bureau of Chemistry and Soils, U. S. Department of Agriculture, Washington, D. C.

USE OF ROSIN SOAP IN INSECTICIDES AND DISINFECTANTS

A soda-rosin soap has certain physical and chemical properties which make it extremely valuable for use in emulsifying oils and as a wetting and spreading agent. Rosin soap in combination with fish-oil soap gives particularly good results. One of the best arsenical cattle dips on the market contains about 8 per cent sodium rosin soap and 2 per cent fish-oil soap. About 130 lb. of rosin are used to each 100 gal. This cattle dip when added to water makes a very fine white emulsion which does not separate on standing.

The efficiency of those insecticides and fungicides which are not soluble in water is dependent largely on the degree of dispersion. Among dispersing agents which increase the effectiveness of copper fungicides, rosin fish-oil soap appears high on the list.

In 1915 the Hygienic Laboratory of the United States Public Health Service published the formula of a pine oil disinfectant which has since become very popular. This formula is as follows: steam-distilled pine oil, 1000 g.; rosin, grade E, 400 g., and 25-per-cent sodium hydroxide solution, 200 g. The pine oil and rosin are heated together until the rosin is all dissolved. The mixture is then cooled to 80° C., the sodium hydroxide solution added, and the liquid violently stirred for at least 10 minutes. Sufficient water is added to bring the mixture to the original weight. The finished disinfectant when added to water makes a perfectly white emulsion, which at low temperatures will persist for weeks. When freshly made, the phenol coefficient of this disinfectant is about 4.5, but after about two months' standing, a noticeable deterioration occurs. On account of the pleasant pine odor of this disinfectant, it has enjoyed a very wide sale in this country.

The present consumption of rosin in the manufacture of insecticides and disinfectants is small, and a great increase in its use for these purposes does not seem likely.

Insecticides, fungicides, and disinfectants of the future will be largely synthetic organic products, and rosin may prove a valuable raw material for the preparation of these. Such a use is only of theoretical interest at present.

[For Discussion on Rosin in Disinfectants, see page 850.]

ROSIN USED TO PRODUCE ROSIN OIL

By V. E. Grotlisch[1]

The discovery about one hundred years ago of the decomposition of rosin on heating, with distillation of a heavy oil, is credited to a French chemist, E. Dive. The French seem to have been the first to give the production of rosin oil much study, due probably to the earlier stabilization of the naval stores industry in France and their greater development of science and industry along these lines. However, we are informed that the chief foreign manufacturers of rosin oil, at present, are in England and Germany and that they consider American rosin decidedly superior to the French product for this purpose. Apparently the manufacture and use of rosin oil in France have not expanded as, according to a report submitted several years ago by a representative of a large American naval stores firm, there were at that time only five manufacturers of rosin oil in France, while in Germany there were more than fifty, all at that time using American rosin.

In this country most of the rosin oil produced is made by a few large firms specializing in this class of material. The consumption of rosin for rosin oil manufacture is more than 25,000 barrels a year.

Rosin oil is a product of the destructive distillation of rosin, with the temperature gradually increasing as the distillation proceeds. The process is carried out usually in a cylindrical cast-iron or steel still, holding from 16 to 30 round barrels of rosin (6500 to 12,000 lb. approximately), and so constructed as to use direct fire under the still and superheated steam coils and jets in the interior. Most rosin oil is made at atmospheric pressure, although we understand that in Germany at least one large plant distills under reduced pressure. Dry rosin, free from turpentine, begins to soften at about 120° F., and becomes a viscous fluid at 140° F. An internal change takes place as the temperature increases, the color becoming darker and some decomposition with liberation of water is apparent at about 250° F. As the temperature increases the decomposition becomes progressively more vigorous, with liberation of incondensable gases and water, and at about 320° F. a light straw-colored sharp-odored liquid called rosin spirits, rosin naphtha, or pinolin, starts to distill. The specific gravity of this crude liquid is above 0.90, but on rectification and redistillation, over alkali, the acidity is reduced and higher boiling constituents are separated, yielding a product having a specific gravity of about 0.850 and which up to 80 per cent distills between 100 and 200° C.

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[1] Office of Naval Stores Control, Food and Drug Administration, U. S. Department of Agriculture, Washington, D. C.

At the end of the rosin spirit stage of the distillation, the temperature of the still must be increased above 400° F., when distillation of a light yellow rosin oil, containing some rosin spirits, commences. This stage, yielding about 6 per cent of distillate, is soon passed with increase of the temperature to about 480 to 520° F., when the "hearts" of the distillation, the so-called "kidney oil," is obtained. It is this kidney oil that is the real meat of the distillation. It has not only the highest value as such but also is the product which is used for producing the best quality of redistilled rosin oil.

Kidney oil runs high in undecomposed abietic acid, containing from 40 to 56 per cent free acid, depending on the speed of distillation, the design of the still, and the kind of rosin used. Its composition may be varied according to the use to which it is to be put. Ordinarily the acid content does not exceed 50 per cent. This kidney oil has a specific gravity slightly above 1.000, and contains some emulsified water. On standing it usually darkens somewhat and crystals of abietic acid separate. The water may be removed by heating in an open kettle.

Toward the end of the distillation the oil becomes darker and takes on a greenish fluorescence. This is called "bloom oil" and usually amounts to about 15 per cent of the distillate. The acidity of bloom oil is less than that of the kidney oil, but depends somewhat on when the "cut" from kidney to bloom oil is made. Ordinarily bloom oil contains not more than 20 per cent abietic acid. The distillation is stopped when the temperature reaches 680° F. The residue is rosin pitch.

The principal uses of genuine rosin oil are in the manufacture of greases, such as axle and cup grease, and of printing ink. The grease maker uses the kidney oil principally, because the high free acid content of this oil takes up a large proportion of alkali, forming a rosin soap. This soap, which has lubricating qualities, also combines with and holds in suspension a maximum of mineral oil. Some cheap dark-colored greases are made with a proportion of bloom oil, where greases having a quick set, high stability, and light color are not of great importance. For some special purposes the traces of moisture in kidney oil must be removed by heating in open vessels.

For the cheaper grades of printing ink, as for newspapers, first-run oils are used, especially for mixing with rosin, drying and petroleum oils, to form the so-called "rosin oil varnish." Better quality book and lithograph inks require a thinner, less acid oil, and for this purpose a second or third run oil is used. The better second-run oil is made by redistilling kidney oil, while for the cheaper second-run oils almost the entire rosin oil obtained on the first distillation is used. The loss on redistilling rosin oils amounts roughly to 10 per cent, while the loss on the first distillation runs above 10 per cent. It will readily be seen that the higher run oils are necessarily more expensive.

Rosin oils, mostly of the higher runs and greater refinement, are also used in varnishes, cable insulation, transformer oils, lubricants, shoe polish, belt dressings, brewer's pitch, oil-cloth and linoleum, core oils, and numerous other products. Consumers of rosin oil usually have special requirements so that rosin oil manufacture is largely on a specialty basis, making oils to meet requirements of individual consumers.

As has been stated, American rosin is generally used, the preferred grades being E, F, and G gum rosin. For some special light-colored oils higher grades are sometimes used, but the higher cost of the lighter colored rosins makes their use very limited. Rosin oil makers claim that the higher grades do not produce as much oil nor oil with as high acid content, on first distillation, so that for ordinary rosin oil production the better common grades are used. Competition and high rosin prices also cause the rosin oil maker to turn to the lowest grades of rosin, B and D. In fact, the manufacture of rosin oil is the principal outlet for these bottom grades. However, the low grades are usually not very clean or well strained, and the rosin oil manufacturer using them must exert extra precaution against excessive dirt and the burning out of his still, or having a worthless pitch left, due to formation of a solid cake of sand and charred carbonaceous residue on the bottom of the still. Therefore, careful examination must be made of the raw material when the lowest grades of rosin are used. Grade B rosin also is claimed to give a darker oil and a lower yield of oil with more of the bloom oil than the better "commons."

Rosin oil manufacturers are to some extent mixing wood rosin with gum rosin for certain special rosin oils. For high grease set, straight gum rosin oils are considered best. As stated before, rosin oil is a speciality product, with various consumers using different oils for apparently similar purposes. Rosin oil made from straight wood rosin has a slightly different odor from gum rosin oil, shows a peculiar reddish color, and a tendency to darken rapidly on standing, becoming opaque and developing excessive bloom. The ordinary grade FF red wood rosin is the grade of wood rosin usually used.

A grade of rosin which finds little use for other purposes is utilized by the rosin oil maker. This is what is known as opaque rosin, for which an official grade, designated by the letters "OP," has been established under the Naval Stores Act.

Opaque rosin is clean rosin of any color, which on account of lack of transparency can not be accurately described and graded by one of the usual grades. There are two kinds of opaque rosin, one caused by presence of water and the other by excessive separation of crystals of abietic acid. Water opaque rosin appears like a solid yellowish emulsion, and breaks with a smooth shiny face. Crystal opaque rosin is grainy and gritty, and breaks with a dull rough surface. Water opaque rosin usually results from incomplete distillation of the gum, whereas crystal opaque rosin is the result of conditions not clearly understood. Among these is the introduction of water into the rosin during cooling, after it has been drawn from the still and dipped into the barrels. This often happens where a severe rain and windstorm occurs, the rain blowing in under the still shed or coming through a leaky roof shortly after drawing off a charge. Another cause is the agitation of the rosin when it has cooled almost to the solidifying temperature. If rosin is allowed to remain in the vat too long before it is dipped, the last portions will have begun to solidify by the time they are dipped into the barrels, and crystallization may take place. Introduction of this crystallizing pasty rosin will sometimes cause the balance of the rosin in the barrel to become more or less crystallized. Sometimes moving or violently jarring a barrel of rosin, when it has cooled to a certain extent, will cause crystallization. Throwing down and rolling the barrels before the rosin has solidified will also cause it.

The rosin oil maker need have no serious trouble with crystal opaque rosin, since he melts it and heats it far above the cracking point. The water opaque rosin can be freed from water by careful heating at the start. This must be done slowly and cautiously as the water causes the molten rosin to foam badly. After the water is driven off and the foam subsides, the distillation proceeds normally. Opaque rosins generally are of the medium and better grades, and therefore, are usually clean.

On the other hand, for making rosin oil varnish or the so-called "synthetic" rosin oils using undistilled rosin along with mineral, paraffin, or other oils, or for specialty oils which are compounded with free rosin, a line which most rosin oil makers usually carry also, the use of opaque rosin must be avoided. Even rosin which merely shows a tendency to crystallize, as indicated by a few isolated crystals in the otherwise clear rosin, must be avoided for some purposes, lest the entire rosin content crystallizes into semi-solid pasty mass. This is true of what are known as core oils and gloss oils.

In general, then, the rosin oil manufacturer prefers fairly clean, American gum rosin, having a maximum acid number (abietic acid), and a low unsaponifiable residue. This is obtained at the most attractive price in grades E, F, and G, which contain, by and large, for the cost of the rosin, the highest acid content and low unsaponifiable matter, such as resenes, turpentine fractions, and pitchy matter, and are usually clean enough to distill without danger of affecting the still or the products.

[For Discussion on Rosin in Rosin Oil, see page 851.—ED.]

THE USE OF ROSIN IN CORE OIL

By Werner G. Smith[1]

Actual figures for the consumption of rosin in core oil are not available. According to our estimate there are approximately 44,000 barrels of rosin consumed annually in the core oil industry.

Core oils are composed of drying oils, rosin and mineral thinning oils. Core oils contain up to 38 per cent of rosin by weight. Core oil, in which rosin plays an important rôle, is used by gray iron, steel, brass and aluminum foundries in the process of casting metals into required forms. The oil is mixed with sand in varying proportions and molded into desired shapes in core boxes. The resulting cores are dried in ovens, placed in sand molds in the foundry and form the interior of the finished casting after the molten metal is poured into the mold around the core.

The function of a core oil is to bind sand into a hard form of any required shape. Before drying, core oil has no adhesive strength. It acquires its strength when oxidized into a dried film. This oxidation is accomplished in ovens at a temperature of approximately 450° F.

Tensile strength is of chief importance in core oil, but a core must be porous and contain a minimum of gas producing material. Rosin is germaine in our subject in that it affects the amount of gas produced, the porosity of the core, the manner in which a core holds its shape as the core is cooled when it comes from the oven, the contraction and expansion of the film of the core oil as the core is baked in the forms or core driers and to some extent the manner in which a core is destroyed in the casting after the molten metal is set.

Rosin by itself has very little tensile strength when made into a core. As compared with linseed oil—a ratio of one part rosin to fifteen parts sand by volume equals a ratio of 80 parts sand and 1 part linseed oil by volume. While rosin used alone is deficient in tensile strength, it accumulates strength when mixed with drying oils. For example, a mixture of 40 parts rosin, 55 parts neutral mineral oil and 5 parts raw linseed oil is equal in tensile strength to 10 per cent of raw linseed oil. Fifty per cent of the above mixture with an equal quantity of linseed oil is the equivalent of 90 per cent of the tensile strength of raw linseed oil. In our opinion, in combination with linseed oil 2 parts of rosin is equal to 1 part linseed oil in tensile strength.

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[1] President, The Werner G. Smith Co., Cleveland, Ohio.

For most economical use, the ideal sand in making cores is a clean, sharp silica sand or lake sand, such as is found along the southern shores of Lake Michigan. It should be free from loam or dirt. On account of shapes and sizes of some cores, foundries must use sand containing greater or less amounts of loam. In such mixtures rosin is of most value. In clean, sharp sand a core oil covers the surface of each grain of sand and is not absorbed by the sand. During baking the oil is drawn by capillary attraction to the points of contact of the grains and is oxidized or dried into a hard film—firmly cementing the grains together, and by being drawn to the points of contact the interstices or spaces between the grains are left open, which permits the escape of gas formed when the molten metal comes in contact with the core. In loamy or dirty sand the interstices are largely clogged with particles of dirt which absorb the oil—not only wasting oil but reducing the porosity of the core. Rosin in core oil not only retards absorption by loamy sand but is of value to the industry by being one of the cheapest binding materials usable in core oil.

Grading of rosin is essential to the core oil industry as indicating the cleanliness of the rosin and the preservation of standard colors in the finished core oil. Considerable variation in acidity and saponification values of given grades of rosin are experienced. This variation is compensated for in the core oil industry by the use of a number of barrels to one charge. Color in core oil is essential only in satisfying the prejudices of foundrymen, who feel that in amber colored core oils they can more readily detect changes in raw materials used by the manufacturer. The popular grades of rosin used by core oil manufacturers are grades H, I and K.

Cores are baked in ovens at 350 to 550° F. for periods of time varying from one to several hours depending upon the size and shapes of the cores, grades of oil used, efficiency of the ovens, etc. In this baking process, 15 to 20 per cent by weight of the linseed oil, 20 to 25 per cent by weight of the rosin, and the volatile mineral oils used as thinners are driven off as gas and smoke.

Rosin is comparatively easily destroyed by molten metal and for this reason is particularly well adapted for use by brass and other non-ferrous foundries where the temperature of the metal is low compared to gray iron or steel foundries and the castings are generally small.

Conclusion:

Rosin is primarily used in core oil because it is cheaper than drying oils, synthetic or fossil gums, and the extent of its use is determined by its cost and binding values compared with drying oils and competitive gums. The core oil industry pays for and loses approximately eighty pounds of wood in each round barrel of approximately 500 lb. of rosin. The elimination of this loss would undoubtedly stimulate the use of this rosin. We believe some of this loss can be eliminated by the shipment of rosin in tank cars and we believe without injury to the core oil industry the melting point of rosin could be raised to a point permitting the shipment of rosin in bulk—either in box cars or gondolas. We believe, also, the consumption of rosin can be increased in the core oil industry if the producers of rosin could devise ways and means to increase the tensile strength.

[For Discussion on Rosin in Core Oils, see page 851.—ED.]

DISCUSSION ON ROSIN

ROSIN IN ROSIN ESTERS

MR. V. E. GROTLISCH.[1]—Last week in New York I learned of two lots of apparently perfectly made rosin, high-grade rosin, which were apparently dry to all outward appearances, which were rejected by an ester gum manufacturer because he said it would not make the grade of ester desired. Mr. Babcock brings out the point in his paper that apparently it is the presence of volatile matter in the rosin which has something to do with the darkening effect when the rosin is converted into ester gum, and I think that that is something that should be carefully studied by all ester gum maufacturers, who have any trouble, to see if they can locate what the trouble is. If it is volatile matter, then there should be a standard test for determining volatile matter in rosin, but these two lots of rosin were apparently perfectly made. There was no sign of anything being wrong with the rosin.

MR. STEPHEN BABCOCK.[2]—Do you know what the acid number was?

MR. GROTLISCH.—I do not know. In one case it was a mixed 100-barrel lot in which the rosin came from a number of producers. Two different batches of ester gum were made, and the manufacturer declared that it would not meet the specification and asked that the rosin be replaced. The other was rosin from a single source, and we have some samples of that rosin and can and will determine the acid number. It is apparently dry rosin.

MR. P. H. WALKER.[3]—I should like to ask whether pale rosins do have more volatile matter than dark rosins.

MR. GROTLISCH.—They frequently do, because the manufacturer of rosin is afraid to carry the distillation as far as he might, because it is just the short length of time at the end of the distillation which may cause darkening, and the tendency is to leave more volatile matter in the high-grade rosin than is done on the lower grades. A good manufacturer can make high-grade rosin without leaving any more volatile matter in than he does on the lower grades.

MR. J. M. SCHANTZ.[4]—I should like to suggest the determination of the petroleum ether insoluble content of rosin. Oxidized rosin darkens when heated to high temperatures. The petroleum ether insoluble is a good indication of oxidized rosin content.

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[1] Office of Naval Stores Control, Food and Drug Administration, U. S. Department of Agriculture, Washington, D. C.

[2] John D. Lewis, Providence, R. I.

[3] Chemist, U. S. Bureau of Standards, Washington, D. C.

[4] Technical Service, Naval Stores Department, Hercules Powder Co., Wilmington, Del.

MR. GROTLISCH.—Referring to Mr. Schantz' statement, one of these lots was freshly made rosin, and apparently there was no chance for any oxidation to have taken place.

MR. G. F. KENNEDY.[1]—Referring to the remarks of the last speaker, I think it would be quite impossible to produce unoxidized rosin. Even in the production of pure abietic acid one needs to be very careful to avoid oxidation, and even if extreme precautions are taken one will always find that partial oxidation.

ROSIN IN PAINTS AND VARNISHES

MR. WALKER.—I should like to ask Mr. Hopkins how the viscosity of rosin is to be determined.

MR. F. W. HOPKINS.[2]—I do not believe that there is any standard method for determining the viscosity of rosin. It would be possible to make a cold cut of rosin in a solvent such as toluol, and to determine the viscosity of such a solution through one of the standard viscosimeters, or by the Gardner-Holdt viscosity tubes. I believe that this would give a relative viscosity, or difference between two batches of rosin. Of course, we are interested in the softening point at the same time, as well as the fluid or flow point. Nevertheless, I believe that the viscosity of rosin is very important, as some rosins might increase or decrease the viscosity of the finished material. Although we may have two varnishes of the same solid content, it is possible that if two different rosins were used, varying greatly in viscosity, there would be a great deal of difference as far as the application of such varnishes is concerned to various surfaces, because of the difference in viscosity.

MR. C. F. SPEH.[3]—I should like to call attention to *Bulletin No. 1* issued by the Pine Institute which contains abstracts of the work that has been done on rosin in synthetic resins. Copies may be secured upon application to the Pine Institute of America.

MR. HOPKINS.—I am wondering what the consensus of opinion is regarding the acid number, and especially the softening point of rosin, as I have suggested for a suggested specification. The acid number I have suggested is 160 to 170 and the softening point is 150 to 180° F.

THE CHAIRMAN (*Mr. F. P. Veitch*[4]).—I imagine that since the softening and melting points are not, as I understand, exactly the same thing, what you mean by melting point is the point at which the rosin is fluid and flows readily.

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[1] Hercules Powder Experiment Station, Kenvil, N. J.

[2] Assistant Manager, Technical Department, Murphy Varnish Co., Newark, N. J.

[3] Secretary, Pine Institute of America, Jacksonville, Fla.

[4] Chemist in Charge, Industrial-Farm Products Division, U. S. Bureau of Chemistry and Soils, Washington, D. C.

MR. HOPKINS.—I mean first the softening point, and then the fluid point, but, of course, it is the softening point in which we are more interested. We have been using Mr. Walker's modification of the ring-and-ball test, especially on synthetic resins, and we find it very satisfactory.

MR. W. C. SMITH.[1]—I would like to ask Mr. Hopkins a question. He says that in the heat treatment of rosin it usually darkens, but on page 4 of his paper he states that inert gas may be used; will that prevent darkening?

MR. HOPKINS.—It will prevent darkening to a certain extent; it will almost stop darkening.

MR. SMITH.—In other words, darkening is due to oxidation?

MR. HOPKINS.—It is an oxidation.

MR. GROTLISCH.—In Mr. Hopkins' proposed specification he states, "*Loss on Heating.*—Maximum percentage at a definite temperature for a certain number of minutes, for example 570° F. (300° C.) for 15 minutes." My recollection is that that is too high a temperature. Rosin will start to crack if carried to so high a temperature.

MR. HOPKINS.—I have suggested that temperature for one reason especially. In the manufacture of varnish, temperatures as high as 525 to 575° F. are used with both rosin and ester gum. Not only does a darkening or change in color result, but also a certain amount of loss in the varnish, due to this temperature, especially when using rosin. In the suggestion of such a specification, I have tried to make the tests parallel as nearly as possible conditions which exist when rosin is used in regular production.

MR. GROTLISCH.—In the varnish kettle the rosin is mixed with linseed oil and other oils, but in the examination of rosin by itself it has a greater tendency to break down than when it is in solution in oil. Of course, this temperature may give valuable information, but still I think it is too high to heat rosin by itself.

MR. HOPKINS.—On the other hand, since there is 4 or 5 per cent maximum of volatile matter, that is bound to be lost in the varnish kettle. However, the requirement is only suggested, written more for discussion than anything else.

MR. BABCOCK.—Could not that test be carried out more along the lines of actual procedure by melting the rosin with a certain amount of the oil and then observing the color?

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[1] **Assistant Chemist, Industrial-Farm Products Division, U. S. Department of Agriculture, Washington, D. C.**

MR. WALKER.—It does not matter whether the heating test is good for the rosin or not, if it gives information it is a good thing to put it in a specification. The rosin subjected to test is always ruined anyhow. It is like determining ash. Ash might be of importance but you know that all the material will be destroyed in making an ash determination.

MR. VEITCH.—I should like to ask whether anybody has ever heated rosin to 300° C. even for 15 minutes without getting any darkening at all.

MR. HOPKINS.—Yes, we have heated rosin higher than 300° C.—that is, around 555° F. Some rosin when heated to 300° C. has a tendency to darken, whereas wood rosin bleaches to a certain extent, or becomes paler.

MR. VEITCH.—Was the rosin that bleached a bleached or a specially treated rosin?

MR. HOPKINS.—A specially treated rosin. Of course, it is always possible at those temperatures to use inert gas. We have found with the use of such inert gases that esters do not appear to darken.

MR. SCHANTZ.—Just a word of warning. Rosin can be heated to a high temperature without discoloration, but discoloration may take place as the rosin cools and comes in contact with air at a high temperature. This discoloration will depend largely on the amount of rosin used, the type of container and the area exposed to air. All these things should be considered in the proposed specification.

MR. HOPKINS.—When I spoke about heating rosin at these temperatures, it is only for a few minutes, and the temperature was not held more than 15 minutes, and probably the temperature was lowered when the process was continued.

MR. SCHANTZ.—I should like to ask what type of container was used. The container, I think, is a vital feature.

MR. HOPKINS.—We use both a copper container and aluminum. Of course, there is a danger of using such temperatures with aluminum, but we do it.

MR. SCHANTZ.—For this special purpose, would not a glass container be suitable if a standard of some sort is to be adopted?

MR. HOPKINS.—Yes, and we want to use the same type of apparatus as we are using in production.

ROSIN IN LINOLEUM

MR. R. B. ROHRER.[1]—In considering rosin in linoleum compositions, I wish to refer to the remarks made by Mr. Schantz in discussing the use of rosin in rosin esters. He stated that oxidation decreased the solubility of rosin in petroleum ether. There are a number of references in the literature to the use of solvents such as ether, alcohol, acetone, and petroleum ether to extract linoleum cement and other oxidized films. The results of such analytical methods are interpreted as indicating the extent of oxidation of the oil only. The loss of solubility suffered by the rosin has not been taken into consideration. May I ask Mr. Schantz, therefore, how much oxidation affects the solubility?

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[1] **Chemical Engineer, Armstrong Cork Co., Lancaster, Pa.**

MR. SCHANTZ.—As we understand it, oxidized rosin is insoluble in petroleum ether. Resin acids themselves, as found in rosin, are excellent solvents for oxidized rosin. A test for oxidized rosin should be made with a dilute solution of rosin in petroleum ether so that the solubility effect of the rosin itself is minimized. Our own method calls for 1 g. of rosin to 150 cc. of petroleum ether or roughly one per cent by weight. The solution is allowed to stand over night, then it is filtered, and the amount of insoluble matter actually weighed. There are solvents for oxidized rosin, such as alcohol, benzol and acetone.

MR. ROHRER.—How much insoluble matter is normally found in rosin?

MR. SCHANTZ.—All rosins that we have examined contain oxidized resin acids. Pale grades of gum rosin, I believe, usually contain about 1½ to 2 per cent. Lower grades usually contain larger amounts. Pale grades of wood rosin usually contain less than 1 per cent. Grade FF wood rosin contains from 5 to 10 per cent and normally between 5 and 6 per cent. The amount of oxidized rosin that any rosin will contain will largely depend on how it was obtained, how it was stored, and how it was handled prior to its use. Powdered rosin, when exposed to air, oxidizes rapidly, and rosin broken into small lumps oxidizes on all exposed surfaces. Moisture and light seem to accelerate this oxidation.

MR. ROHRER.—I ask these questions because of the nature of the process in manufacturing the binder, or so-called cement, for linoleums. The rosin is exposed to the air at comparatively high temperature, for example at 100 lb. steam pressure, for sometimes many hours. It is probable also that the oxidized oil may help in the oxidation of the rosin. Hence, if it is that much of a factor, it must be given more consideration in interpreting extraction analyses.

I should like to ask about the darkening that occurs also. Is this due to the oxidation of the abietic acid or to the other materials that normally occur in commercial rosin?

MR. SCHANTZ.—I do not know that I am qualified to answer that question. We know that oxidized rosin or rosin that contains oxidized rosin does darken when heated. Whether this is caused by the fact that the oxidized rosin decomposes is not definitely known. We do know, however, that oxidized rosin does decompose at lower temperatures than unoxidized rosin. We believe that what we call oxidized rosin is chiefly oxidized abietic acid, and we know that oxidized abietic acid will darken when heated. There may be other materials present in commercial rosin that cause a similar discoloration. It seems quite possible that oxidation of linseed oil will help oxidize the rosin, and driers used may accelerate the oxidation of both.

MR. VEITCH.—There has been frequent mention in the discussion of acid number and saponification number. Neither varies widely, even between wood rosin and gum rosin. The number for gum rosins will fall within a certain range of 15 or 20 and wood rosin will also fall within a range of 15 or 20, at the extreme and will usually average a little lower. I wonder if the usual differences between acid number and saponification of different samples or of different grades of rosin are of any practical importance. From the fact that they have been mentioned so frequently one might think they are, but I am still open minded on the subject. I am thinking now about specifications. Is the acid number or the saponification number worth specifying for any use, even soap making or size making?

MR. HOPKINS.—I believe the acid number is important, especially in manufacturing ester gum.

MR. VEITCH.—Would a difference of 10 or 15 points have any significance?

MR. HOPKINS.—I do not believe that much distinction would be made between ten to fifteen points, but generally speaking, I do not believe that the acid number varies more than ten points, on an average. When a rosin is used in the manufacture of ester gum which has an especially low acid number, say below 150, the resultant product of the esterified rosin will undoubtedly be very soft, and it is impractical to use an ester gum which has a low softening point.

MR. BABCOCK.—I think it is very important to have the acid number about 170. When you get below that you are liable to run into difficulty. With rosins of low acid numbers I have found that there is a large loss in yield of the ester gum due to the oils distilling off. Had these oils been removed in making the rosin, the producer would not have had as pale a grading, so when we make ester from such a rosin, we get a dark ester, and we might as well have purchased a darker grade and saved money. I feel that an acid number for the pale grades should be above 158.

ROSIN IN RUBBER

MR. SPEH.—I should like to ask whether Messrs. Winkelmann and Busenburg have worked with a number of samples of the various grades of rosin? We know, for instance, that different samples of G-gum rosin differ in their properties. I wonder if the G-rosin listed is a single sample or an average of a number of samples.

MR. H. A. WINKELMANN.[1]—These are individual samples of rosin which were furnished to us by the manufacturer as being good samples of standard grades of rosin.

MR. SPEH.—It would then be possible that further tests with other samples of rosin of these sample color grades might give results which would change the relative positions in the chart of the various mixtures.

MR. WINKELMANN.—That may be true. Plasticity depends on the way the rubber compound is handled, and you might get differences in plasticity with the same sample of rosin, depending on how the compound was milled. This study presents a relative differentiation between these grades of rosin when handled in the same manner. I am trying to point out differences between rosins and the need for a systematic study of them.

MR. B. H. LITTLE[2].—I should like to ask Mr. Winkelmann if the laboratory tests used by the rubber compounders to test the performance of rubber compounds are sufficiently uniform that they may be used as a guide in working up specifications on rosin for rubber compounding.

MR. WINKELMANN.—I do not think that specifications which have been written to date are really indicative of the value of either gum or wood rosin. Grade B wood rosin which is admitted to be the lowest grade of wood rosin and grades G or WW gum rosins, which are pale high-grade gum rosins, gave the same results with regard to tensile strength, elongation, modulus, oven and bomb aging, and yet the two could not have been used interchangeably, because the B rosin gave a far less plastic and less nervy stock whereas the G and WW gum rosins gave very soft and tacky stocks which could not have been handled in the factory. The processing and handling of the uncured stock must be evaluated carefully and given equal consideration with the properties of the cured products. Rosin is an efficient softener and in many instances less of it should be used when replacing other softeners.

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[1] Palmer Gas Products Corp., Akron, Ohio.

[2] Technical Service, Naval Stores Department, Hercules Powder Co., Wilmington, Del.

MR. SPEH.—I am wondering if Mr. Winkelmann is familiar with or has given any thought to the Naval Stores Act. I bring this up because I would appreciate very much if he has not, that he do so, as shortly there undoubtedly will be a discussion on rosin oil. It has been indicated that a blended rosin oil was thought by the trade to be a solution of rosin in mineral oil, or some such solvent, and that a distilled oil was the only true rosin oil. Is it not true that the rosin oils on the market are mixtures of the two?

MR. WINKELMANN.—The largest volume of rosin oil that is used, which is a blended rosin oil, is a straight solution of K gum rosin in mineral oil. There may be others. I just happen to know that this one is in large use and this type is the one that is always recommended. I would not recommend, from the information which I have and have been able to get, the use of distilled rosin oil. I would recommend the use of blended rosin oil because you are dealing with two variables. You have rosin and you have the oil, and you can control such a mixture so much easier. Distilled rosin oil is something we do not know very much about, at least, we have not done very much work with it.

MR. GROTLISCH.—I believe Mr. Winkelmann made the statement that supposedly genuine rosin oils have been offered with as high an acid value as 155. That seems to me impossible, because a kidney oil, a high acid content kidney oil on the first distillation would contain only about 55 per cent of rosin acid, and if the acid value of straight rosin is 160 and the oil was only 50 per cent rosin acid, the present acid value of 155 would not be possible.

MR. WINKELMANN.—The sample was offered as a distilled rosin oil, and with such a high acid number it would probably contain some rosin to account for such a high acid number. We did not know the conposition but it was supposed to have been a distilled rosin oil.

ROSIN IN CABLE IMPREGNATING COMPOUNDS

MR. SPEH.—Referring to the question raised by Mr. Millwood in his paper, I should say unquestionably a consumer of rosin would stand better chances of getting a rosin meeting certain requirements today than he would ten years ago, but that does not mean that he would stand very good chances of getting it. It means that the industry is beginning to realize the need of studying its products and devising ways and means of bringing its products to meet those requirements. Unfortunately, the industry is not a technical industry, and we have had to depend to a considerable extent on the consumers to point out what problems have existed, but I think that all those who have been watching the industry, in the last few years particularly, will recognize that there is a decided trend that way. That is particularly true of the wood rosin industry. The producers of gum rosins are rapidly coming to realize that we have an entirely different condition than have the producers of wood rosins, but just this is going to make the industry change radically its method of handling its products and its method of production. It is going to be on a different scale and under conditions which can control these properties, so that I would say we are going to find increasing chances to obtain products meeting certain requirements.

MR. J. P. MILLWOOD.[1]—My query was not for the last ten years. I had reference to changes during the last four years, not ten years. There has been a great improvement in ten years but I have not seen much in the last three or four years.

MR. VEITCH.—There has been improvement in the last four years even, and I would say that the biggest change has come within the industry in the last two years.

MR. MILLWOOD.—I should like to ask Mr. Speh if he could provide me with the statistics, which I have been unable to get, as to the amount of rosin consumed yearly in the cable industry, or advise where they may be obtained.

MR. SPEH.—We would have to turn to the Census Bureau as the source for this information.

MR. KENNEDY.—Commercial abietic acid is not graded according to color but according to electrical, physical and chemical characteristics. It is a special product made from rosin, and the test of most interest is the low percentage of material insoluble in petroleum ether, which is an indication of the removal of the oxidized rosin.

ROSIN IN DISINFECTANTS

MR. SPEH.—There is an increasing consumption of products which are made based upon the formula for soluble pine oil—a rosin soap dissolved in pine oil referred to in Mr. Roark's paper. The manufacturers, however, pay little attention to the particular properties of the rosin itself, other than any interest which might lie in its value for making soap. The melting point makes little difference to them unless it indicates soap making value. These rosin soaps are also used in formulas other than those using pine oil by using some other germicide.

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[1] Chief Chemist, The Okonite Co., Passaic, N. J.

ROSIN IN ROSIN OIL

MR. E. C. HOLTON.[1]—I would like to ask Mr. Grotlisch, in the distillation of rosin oil, how much rosin spirit is obtained, and what is done with that more volatile portion of the rosin spirits?

MR. GROTLISCH.—The rosin spirit fraction, roughly, amounts to about 3 to 5 per cent. It is refined by redistilling over alkali, and is used as a cheap solvent, replacing turpentine and other thinners, and, I should say, its largest use would be in wood impregnating, such as wood stains.

MR. HOLTON.—What is its odor?

MR. GROTLISCH.—It is pretty hard to describe. The odor is distinctive. It does not smell like anything else that I can compare it to. It is not disagreeable when properly refined. It is more penetrating—a little sharper—than that of turpentine.

ROSIN IN CORE OILS

MR. GROTLISCH (*by letter*).—Referring to the paper by Mr. Smith, the melting point of rosin, where it is practically free from volatile matter, as the grades used for core oil usually are, could probably be raised only by changing the nature of the rosin itself, as for instance, partial neutralization of the acids with lime, making the so-called "limed rosin." Even in such a case, the inflammability of the rosin would be reduced but little, and at least one large railroad handling large quantities of rosin has refused to publish rates or consider the shipment of rosin in bulk in a box car. Gondolas would be out of the question due to danger of fire from sparks or malicious mischief on the part of irresponsible persons.

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[1] Chief Chemist, Department of Executive Research, The Sherwin-Williams Co., Cleveland, Ohio.

PROCEDURE USED BY THE FOREST PRODUCTS LABORATORY FOR EVALUATING PAINT SERVICE ON WOOD

BY F. L. BROWNE[1]

SYNOPSIS

The object of this paper is to describe the procedure used by the Forest Products Laboratory for evaluating paint service on wood. Evaluation of paint service in paint tests involves three steps: description of the changes that take place in the coatings during exposure, rating the extent of the changes, and interpretation of their significance in terms of the practical serviceableness of the coatings. In the past, the third step, interpretation, has been largely neglected but the new point of view from which the tests of the Forest Products Laboratory are conducted made it necessary to pay particular attention to it.

The three indexes of serviceableness are defined: (1) appearance, which measures the ability of the coating to hide the underlying surface and maintain an arbitrarily chosen color; (2) integrity, which measures the ability of the coating to remain intact as a continuous film covering the surface; and (3) protection, which measures the ability of the coating to protect the wood from weathering. Failure in one of the three measures of serviceableness necessitates repainting and therefore determines the durability of the coating.

Besides the indexes of serviceableness, supplementary information concerning qualities and defects of the coating is collected during inspections for the purpose of throwing light upon the course of the observed changes in the indexes of serviceableness. The qualities gloss, hiding, color, cleanliness, and uniformity bear upon the appearance of the coating, while the defects chalking, checking, crumbling, cracking, slitting, flaking, and scaling bear upon its integrity.

In each of the indexes, serviceableness is rated either good, fair, poor, or bad at inspections. These ratings are defined in such a way that they can be kept in mind permanently, so that results of inspections at different times or places can be compared.

The static records of successive inspections are expressed dynamically in terms of the length of time the coating remained in the different ratings. Arbitrary rules are then adopted for defining the durability of the coating based upon consideration of integrity only, and upon consideration of protection as well as integrity, and for giving the lowest rating in appearance and the age of the coating when it was attained.

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In a study of the painting characteristics of woods begun in 1924 (1, 2, 3, 4)[1] the Forest Products Laboratory adopted a systematic procedure for evaluating exposure tests of painted wood that differs materially from methods used by other investigators. This was necessary because the older methods did not seem well adapted to the objectives and point of view of the new investigation. The primary concern was the influence the character of wood exerted on the behavior of the paint applied to it and the point of view was that of the consumer rather than the maker of paint. The relative merits of competing paint pigments were of secondary importance. The procedure for evaluation adopted is not essentially new but it is a logical extension of earlier ones, broader in scope and applicable to a wider variety of purposes. It is, nevertheless, comparatively simple and based directly upon requirements of paint coatings in service.

GENERAL CONSIDERATION OF EVALUATION

Paint coatings, during exposure, change in various respects and become progressively less serviceable. Desirable qualities are gradually lost while defects appear and grow worse. Means of measuring the changes objectively are not yet available and they are therefore judged subjectively by inspectors. Personal judgments give rise to differences of opinion and keep observers from agreeing upon an acceptable system for evaluating the serviceableness of coatings. Review of the published records of past tests of paint on wood (8 to 16 and 19 to 23) indicates that the principal effort has been to detect and estimate the extent of all the changes that take place and that very little attention has been paid to the problem of determining the practical significance of the changes or arriving systematically at an appraisal of the serviceableness of the coating.

Evaluation of paint service by subjective inspections involves three steps which may be termed, respectively, description, rating, and interpertation.

Description:

The qualities of paint coatings that change and the defects that appear must first be recognized, named, and defined. Notable progress in standardizing nomenclature (18) was achieved by Subcommittee XVI on Terms Used in Reporting the Condition of Painted Surfaces of the Society's Committee D-1 on Preservative Coatings for Structural Materials, which defined the defects: chalking, checking, alligatoring, cracking, flaking, scaling, blistering, and peeling, and the qualities: gloss, hiding, and color. Blistering and peeling were recognized as results of abnormal conditions of exposure (5).

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[1] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended hereto.

While the descriptions set up by Subcommitttee XVI are plausible and convenient, it should not be supposed that they obviate differences in personal opinion in describing defects (24). For example, in principle, checks are distinguishable from cracks in that the former are fissures that go only part way through the coating whereas the latter go through to the underlying surface. In practice, however, there is yet no way of telling whether fissures are superficial or through, so that one man may record as checks what another sets down as cracks. A tacit convention prevails among some paint technologists of regarding reticulate fissures as checks until flaking begins, when they become cracks, and of considering parallel fissures to be cracks from their beginning. The question is one of fact and must be settled by demonstration, not by convention. Further occasion for differences of opinion arises from the failure of the standardized terms to recognize all changes that take place in painted wood panels during exposure.

TABLE I.—VARIABLE SCALES OF RATINGS.

Scale A	Scale B	Scale C	Scale D		Scale E	
Defect or Quality	Defect or Quality	Defect or Quality	Defect	Quality	Defect	Quality
10	10	10	Absent	Good	Absent	Good
9						
8	9				Slight	Fair
7		9				
6	8				Marked	Poor
5						
4	7	8	Slight	Fair	Complete failure	Bad
3						
2	6					
1		7				
0	5					
		6				
	4		Marked	Poor		
		5				
	3					
		4				
	2	3				
		2				
	1					
		1				
	0	0	Complete failure	Bad		

Rating:

Description is merely qualitative. The inspector requires means of expressing quantitatively the degree to which defects and qualities are revealed. This is done by ratings which are again personal judgments, subject to differences in opinion. Subcommittee XVI recommended that checking, alligatoring, flaking, scaling, gloss, and hiding be rated on a scale of 10, in which 10 indicates absence of the defect or perfection in the quality and 0 indicates maximum of defect or absence of the quality. For chalking and color, Subcommittee XVI suggested verbal terms only, such as absent, slight, and heavy for chalking, and good, medium, and poor for color.

In proposing the scale of 10 ratings the committee did not define the ratings. Experience shows not only that individuals differ in the scales they set up for themselves but that the scale used by any one observer varies from inspection to inspection. Because of that fact, it is common practice for observers to consult the records of previous inspections before setting down their ratings in order to avoid the obvious inconsistencies that would otherwise result in their data. Table I illustrates what is meant by different scales of ratings. The five scales designated scales A, B, C, D, and E are comparable horizontally; thus all start from agreement about perfection in a quality or absence of a defect, but the condition of a defect rated 4 according to scale A is rated, respectively, 7, 8, "slight," and "complete failure" by scales B, C, D, and E. Scales A and E end long before scales B, C, and D because opinions about what constitutes complete failure or bad quality differ that much.

Interpretation:

Records of qualities and defects with their ratings at successive inspections are merely data and do not in themselves disclose the serviceableness of the coating. The data must be interpreted. To do so the observer must reach a clear understanding of the service or services expected of the coating in practical use and appraise its merits accordingly. It is the serviceableness of the coating that is the center of interest; the observed defects and qualities acquire significance only in so far as they alter the serviceableness or indicate how and why it is altered. The investigator can draw conclusions from his tests only by such a process of interpretation, whether or not he realizes that he is doing so and whether or not he does it systematically or impressionistically. To interpret systematically, the services expected of the coating must be clearly defined and either rated directly or deduced by grouping the observed defects and qualities into schedules or indexes corresponding to the services expected.

There are marked differences of opinion about the significance of the various defects and qualities, so much so that many investigators shirk the task of interpretation entirely, leaving it to the readers of their reports to do so, or else they assert conclusions without showing how their data lead to them. Subcommittee XVI did not deal with this step in evaluation except to authorize a rating for general appearance, which was said to "be influenced by such conditions as cracking, scaling, chalking, and other conditions usually found in paint wear," that is, general appearance is one index of the coating's serviceableness. Condition for repainting is another index of serviceableness similarly inferred from rated defects and qualities by many workers.

The author knows of only one systematic attempt to deduce serviceableness from rated defects and qualities. According to this scheme, which is used by the Sherwin-Williams Co., the serviceableness of a coating is measured by the sum of its ratings in five qualities: (1) gloss, (2) freedom from chalking, (3) freedom from checking, alligatoring or cracking, (4) freedom from flaking, scaling, or peeling, and (5) general appearance. A perfect coating receives a rating of 20 in each quality, making a total of 100. The ratings are decreased as changes take place, subject to the restrictions that freedom from chalking retains a rating of 20 until gloss falls to zero and freedom from checking, alligatoring, or cracking becomes zero at once when freedom from flaking, scaling, or peeling falls below 20. The further restriction is imposed that the measure of serviceableness of a coating may be compared only with those for other panels tested simultaneously under the same conditions of exposure.

SALIENT FEATURES OF THE FOREST PRODUCTS LABORATORY PROCEDURE

The Forest Products Laboratory method of evaluation sets up a reasonably simple conception of the practical requirements of a paint coating in service and then keeps that conception uppermost in the observer's mind while making his inspection by obliging him to base his decisions upon it. This direct procedure is believed to secure a more reliable rating than could be obtained by indiscriminately recording ratings for all observable defects and qualities and later deducing serviceableness from them. The defects and qualities are not neglected, however, for the inspector takes them into account, so far as they seem significant, in making his ratings. In addition, he makes supplementary record of them for possible future use whether they seem significant at the time or not. The procedure makes interpretation the inspector's primary duty while providing for miscellaneous observations also.

The conception of the practical requirements of paint service may be stated as follows: (1) The coating must hide the underlying surface and maintain an arbitrarily chosen color, (2) it must remain intact as long as possible in a continuous film covering all of the surface to which it was applied, (3) it must protect the wood from weathering (3) which would roughen the smoothly planed surface and distort the pattern of the woodwork. Repainting may be made necessary by failure in any one of the three requirements depending upon conditions of the exposure or the user's desires. Some people repaint when the coating becomes dirty or faded, some wait for it to flake, and some are wise enough to repaint when the wood shows the need of more adequate protection. Accordingly three indexes of serviceableness are established, called respectively the appearance of the coating, the integrity of the coating, and the protection afforded by the coating.

At each inspection the coating is rated good, fair, poor, or bad in each of the three indexes. These ratings are few enough in number and defined in such a way that the inspector can keep a fairly definite picture of them in mind, making it possible for him to compare successive inspections of the same panel or corresponding panels at widely separated exposure stations.

Such records are static, indicating conditions at the time of inspection only. Practical interest in coatings is dynamic, asking how long the coating remains serviceable. The evaluation is expressed, therefore, in terms of the number of months during which the coating remained good, fair, or poor in each index. Finally rules are adopted for deciding when repainting is needed to maintain the integrity of the coating and to maintain protection as well as integrity, by means of which figures are obtained expressing arbitrarily the durability of the coating.

INDEXES OF SERVICEABLENESS

Appearance of the Coating:

Appearance depends upon the ability of the coating to hide the underlying surface and control the color and gloss. It has nothing to do with the ability of the coating to remain in place and is therefore not to be confused with the index "general appearance" used by Subcommittee XVI. In judging appearance such qualities as opacity, cleanliness, maintenance of original color, gloss, and uniformity are taken into consideration. When a coating becomes dirty or fades it looks much worse if it does so in a spotty fashion than if it remains uniform. Fading is less serious if the faded color is still reasonably pleasing. Although checking has to do principally with integrity, it sometimes mars appearance if it is visible at a reasonable distance from the painted surface.

During the first part of the life of a coating the most significant changes are in appearance. Often the appearance grows rapidly worse, reaches a minimum of desirability, and improves again markedly when chalking sets in because some of the dirt may then be dislodged. If a paint user remains content with the appearance when at its minimum of serviceableness it will be dissatisfaction with either integrity or protection, not with appearance, that will cause him to repaint. Interest in appearance, therefore, is greatest during the earlier stages. After integrity becomes *poor* the inspector no longer records a rating for appearance, both because of the difficulty of judging it when the coating is flaking seriously and because it is no longer significant.

Appearance did not prove very important in a study by the Forest Products Laboratory of the painting characteristics of different woods because the changes in appearance were influenced only very slightly by the nature of the wood. Perhaps differences between woods might have been revealed if two-coat painting practice had been followed instead of three-coat in painting the test panels.

Integrity of the Coating:

Detachment of pieces of coating, laying bare the underlying wood, is charged against the integrity of the coating. Such disintegration always originates in fissures of some kind. Fissures that unmistakably penetrate all the way through the coating are considered imperfections in integrity, but if there is any doubt about their depth they are disregarded in making the rating, although recorded as supplementary information. The sole criterion for judging integrity is the exposure of wood that was initially covered by coating.

When wood checks appear where the coating is still intact, a crack forms in the coating coinciding exactly with the check in the wood. Such cracks are not charged against integrity unless the coating curls up along the edges. The wood checks are evidence of inadequate protection, not of failure of the coating to remain intact, for the fissure does not lay bare any wood that was initially painted. Similarly the tearing of a coating over the joint between two tightly abutting boards when the boards shrink is not a failure in integrity.

The size and pattern of the pieces in which a disintegrated coating sloughs from the wood is not considered in rating the integrity. The amount of wood laid bare is the important point.

Ordinarily failure in integrity does not set in until the latter part of the coating's life. When it does it becomes progressively worse and the nature of the wood has a great deal to do with the rate at which deterioration proceeds. Integrity was a matter of prime importance in studying the painting characteristics of woods. There can be no question about the need for repainting when the coating is badly disintegrated.

Protection by the Coating:

The effectiveness of coatings as protective agents against wood weathering can be determined by objective measurements (6) provided that suitable arrangements are made for subjecting the panels at intervals to the necessary test. However, the actual occurrence of weathering defects depends both upon the effectiveness of the coating and the amount of protection required by the painted boards. Since evidence of wood weathering is often observed before the coating has deteriorated very badly, a record of it becomes an essential part of a test of paint on wood.

Wood checks are usually the first observable development in the weathering of wood either exposed without protection or covered with a coating that is no longer furnishing adequate protection. Cupping of boards and pulling loose at fastenings generally take longer to develop. Consequently the principal basis for judging protection usually proves to be wood checking, but cupping or loosening at fastenings, if they occur, are considered very serious defects belonging to this category.

Wood checks are charged against protection only when they are observed in areas on which the coating is still substantially intact because it is obvious that protection is inadequate where the coating has gone and the wood is bare. No rating for protection is recorded after integrity has been judged poor, for much the same reason.

Loose grain, that is, the separation of one annual growth ring in the wood from the next ring, is recorded separately as supplementary information and is not charged against integrity. Boards whose grain loosens easily may develop loose grain very quickly and it is doubtful whether paint coatings can be relied upon to prevent it.

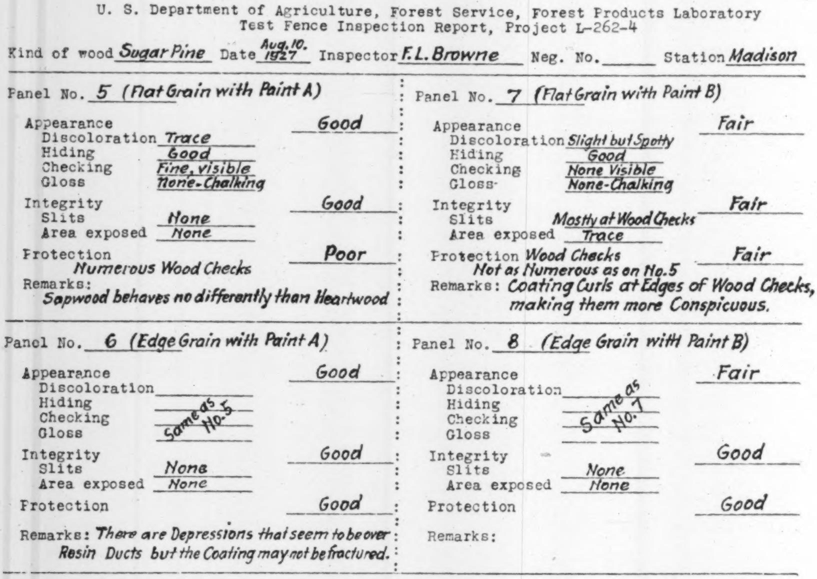
Like integrity, protection usually does not deteriorate seriously until the latter part of the coating's life, but once started it becomes progressively worse. Evidence of inadequacy in protection may often be observed before disintegration of the coating becomes marked. The damage done by delaying repainting after wood weathering sets in is permanent because paint does not restore a roughened surface to a smoothly planed condition nor straighten a cupped board.

SUPPLEMENTARY INFORMATION

On the forms of record for inspections of test panels there are, beside the spaces provided for the ratings in each of the three indexes of serviceableness, spaces for describing specific defects and qualities of the coating. These descriptions are grouped under the indexes to which they are considered most closely related.

Description Used in Earlier Tests:

Figure 1 illustrates the form adopted for tests started in 1924 and the manner of using it. Under the index "appearance" supplementary information shows that panel No. 7 was considered less satisfactory than panel No. 5 because it was somewhat dirtier and particularly because it was unevenly discolored, or "spotty." The fine paint checks on panel No. 5 were not conspicuous enough to mar the appearance.



U. S. Department of Agriculture, Forest Service, Forest Products Laboratory
Test Fence Inspection Report, Project L-262-4

Kind of wood Sugar Pine Date Aug. 10. 1927 Inspector F. L. Browne Neg. No. ____ Station Madison

Panel No. 5 (Flat Grain with Paint A)
Appearance Good
Discoloration Trace
Hiding Good
Checking Fine, visible
Gloss None-Chalking
Integrity Good
Slits None
Area exposed None
Protection Poor
Numerous Wood Checks
Remarks:
Sapwood behaves no differently than Heartwood

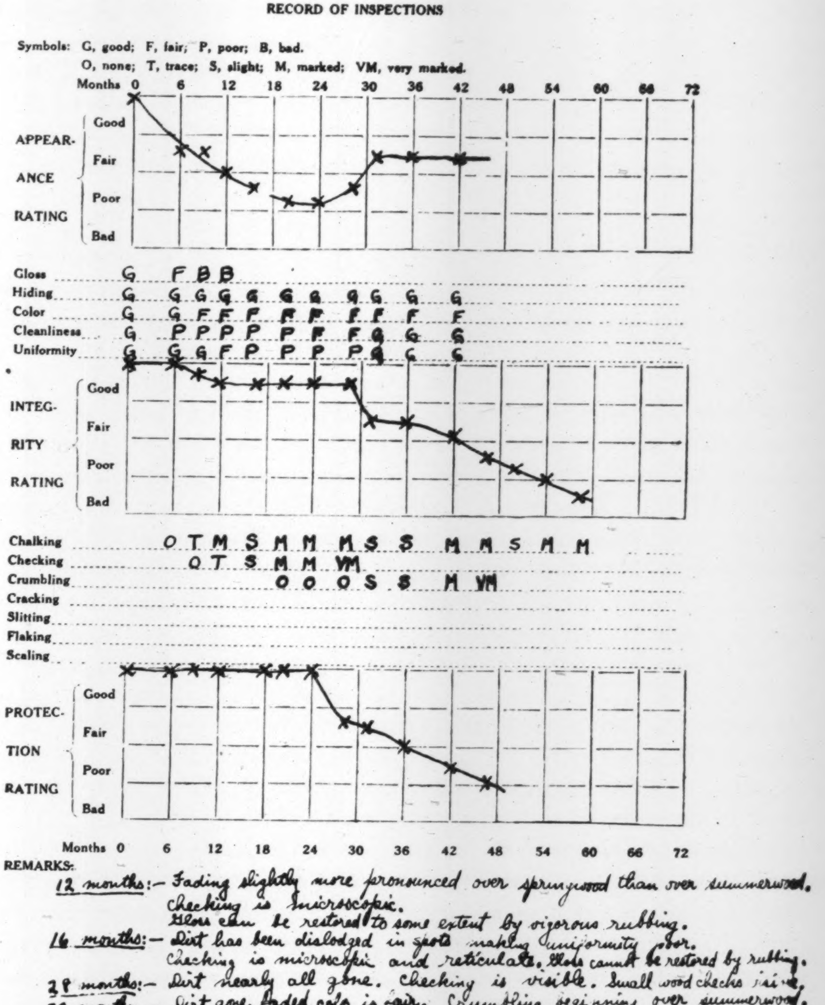
Panel No. 6 (Edge Grain with Paint A)
Appearance Good
Discoloration
Hiding
Checking
Gloss
Same as No. 5
Integrity Good
Slits None
Area exposed None
Protection Good
Remarks: There are Depressions that seem to be over Resin Ducts but the Coating may not be fractured.

Panel No. 7 (Flat Grain with Paint B)
Appearance Fair
Discoloration Slight but Spotty
Hiding Good
Checking None Visible
Gloss None-Chalking
Integrity Fair
Slits Mostly at Wood Checks
Area exposed Trace
Protection Wood Checks Not as Numerous as on No. 5 Fair
Remarks: Coating Curls at Edges of Wood Checks, making them more Conspicuous.

Panel No. 8 (Edge Grain with Paint B)
Appearance Fair
Discoloration
Hiding
Checking
Gloss
Same as No. 7
Integrity Good
Slits None
Area exposed None
Protection Good
Remarks:

FIG. 1.—Form Adopted for Recording Inspection Data for the Tests Started in 1924.

Under the index "integrity," spaces are provided for supplementary information concerning slits and area (of wood) exposed. Slits are cracks (in the sense defined by Subcommittee XVI) that are parallel to the grain of the wood and at the edges of which the coating curls outward. They look much as though a knife cut were made at a place where the coating did not adhere firmly to the wood. Slits appear suddenly and do not grow from checks. They are often, though not always, associated with wood checks but the fissure in the coating may not coincide with that in the wood and a small area



REMARKS:

12 months:— Fading slightly more pronounced over springwood than over summerwood.
Checking is microscopic.
Gloss can be restored to some extent by vigorous rubbing.
16 months:— Dirt has been dislodged in spots making uniformity poor.
Checking is microscopic and reticulate. Gloss cannot be restored by rubbing.
28 months:— Dirt nearly all gone. Checking is visible. Small wood checks [illegible].
32 months:— Dirt gone, faded color is fair. Crumbling beginning over summerwood.
36 months:— Microscope shows that checks are through to wood.

FIG. 2.—Form for Recording Inspection Data Adopted for Tests Started in 1929 and 1930.

To illustrate its use fictitious entries have been made showing the course of events for an imaginary test panel.

of initially painted wood is left bare. Slits occur far more frequently over summerwood than over springwood. Slits should be distinguished from cracks that grow from reticulate checks because they evidently originate in a different way. There are other types of paint cracks, which did not occur in the earlier tests by the Forest Products Laboratory, for which no places were provided in the form. Area of wood exposed refers to the practical result of flaking or scaling but without regard to the size or shape of the paint flakes or scales themselves.

Descriptions Used in Later Tests:

As the investigations of the Forest Products Laboratory continue, primers and paints of different composition are being tested, thus increasing the variety of coating defects to be dealt with. More adequate provision for supplementary information on the record form therefore seems desirable although such details of paint behavior do not influence the method of rating the three indexes of serviceableness. Figure 2 shows a new form adopted for tests started in 1929 and 1930. The records of all inspections throughout the history of a test panel will be collected on this form. The ratings for appearance, integrity, and protection will be plotted graphically against the age of the coating, following the method devised by the E. I. du Pont de Nemours and Co. and the Grasselli Chemical Co. (17).

Beneath the graph for appearance, spaces are provided for five qualities: gloss, hiding, color, cleanliness, and uniformity. The first two have the same meaning given them by Subcommittee XVI. Color is the quality corresponding to the defect usually called fading. Cleanliness means freedom from discoloration with dirt. Uniformity describes the even or spotty distribution of dirt and of fading.

Beneath the graph for integrity are spaces for seven defects: chalking, checking, crumbling, cracking, slitting, flaking, scaling. Checking includes not only the fine, reticulate fissures now generally known by that term but also fine, parallel fissures that are not demonstrably through to the wood when first seen. Fissures, which were once called checks, retain that designation even though ultimately they open wide enough for the microscope to reveal the wood through them. The inspector should indicate whether checks are reticulate or parallel, microscopic or visible, and whether the wood can be seen through them. Crumbling is the ultimate development of checking, in which pieces of coating outlined by checks fall off bodily, leaving the wood bare. Parallel checks, of course, become reticulate before they result in crumbling. Cracking refers to fissures through which bare wood can be seen when the defect is first observed, but at the edges of which the coating does not curl promptly, as it does in slitting, which has already been defined. Cracks to begin with are much longer fissures than checks; they tend to lie generally parallel to each other but may be either approximately parallel or at right angles to the grain of the wood, and they are often curved at the ends giving them roughly an ogee shape. They look much like rents caused by an external force of tension upon the coating. Long cracks may result in scaling, which is defined as disintegration of the coating in pieces large enough to lay bare springwood as well as summerwood. Shorter cracks result in flaking, in which the pieces of separated coating are smaller and at first lay bare summerwood only. Breaking off of the curled edges of coating at slits is also flaking.

RATINGS

If the ratings for the indexes of serviceableness at successive inspections or of corresponding panels at widely separated stations are to be compared with each other it is essential that the scales of ratings be defined in reasonably permanent fashion. The scales consist of four ratings only, good, fair, poor, and bad. Obviously much finer distinctions can often be drawn among the members of a group of panels being observed side by side, but the finer distinctions cannot be detected if the observations are separated in time or in space. A scale with too many degrees is therefore illusory.

Appearance.—In appearance, the rating good permits a moderate departure from the original cleanliness and color provided that the appearance remains sensibly uniform and is still pleasing. Moderate but somewhat irregular change in cleanliness or in color, or fairly marked but uniform change in either quality calls for a rating of fair. Marked irregularity in cleanliness or color, somewhat displeasing color, or marked though uniform change requires a rating of poor. Very irregular cleanliness or color, displeasing color, or very marked though uniform departure from the original appearance is rated bad.

Integrity.—The integrity of the coating is rated good if no bare wood can be seen through checks, cracks, slits, crumbling, flaking, or scaling of the coating. If there is any bare wood at all the rating must be lower than good. The rating is fair if the microscope is necessary to reveal the bare wood, or if the bare wood is visible to the unaided eye but the breaks in the coating are few in number and the coating is still intact over considerable areas of the panel. The rating is poor if bare wood, visible to the unaided eye, is observable in all parts of the panel or if some of the bare areas are conspicuous. Conspicuous bare areas in many parts of the panel require a rating of bad. Figure 3 shows test panels illustrating typical conditions described by the ratings in integrity.

Coatings are rated for integrity only over areas of clear lumber. Fissures or fractures over knots, pitch pockets, or pitch streaks are recorded separately as supplementary information. Similarly, disintegration of the coating near the ends of boards, especially if near end checks in the wood, are given little consideration.

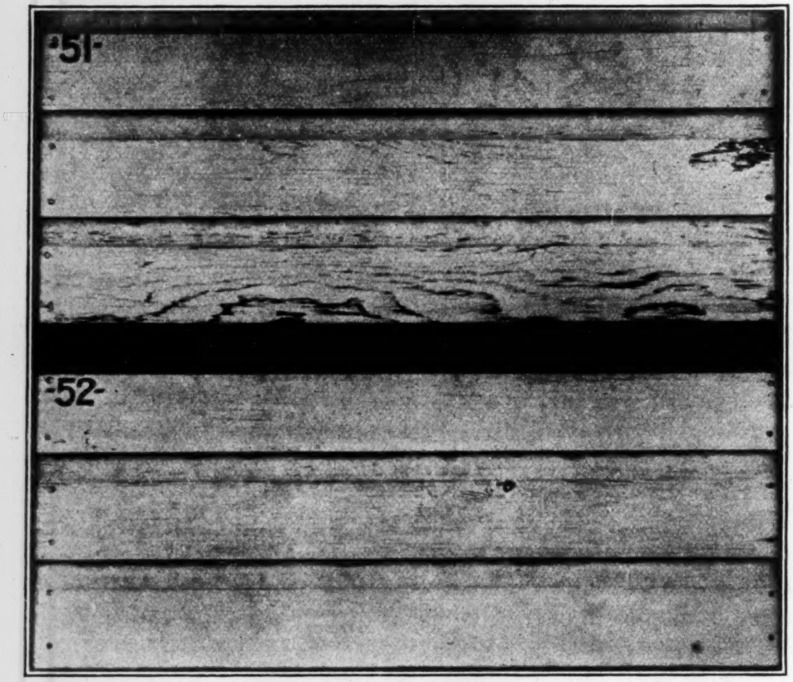


FIG. 3.—Illustrating the Ratings for Integrity.

Panel No. 51 was rated bad. Panel No. 52 was rated poor. The slight crumbling or flaking that would occasion a rating of fair can scarcely be seen in a photograph showing the whole area of the panel.

This scale reaches the rating "bad" while most of the original coating still remains in place. With further weathering the coating would slough off more completely, but there is no point in continuing the test after the coating has become clearly unserviceable on the score of bad integrity.

Protection.—In protection the coating is rated good if there is no evidence of wood weathering in any part of the panel where the coating is still intact. A few small wood checks requiring careful examination to detect call for a rating of fair. Such checks may not be observable at all if the surface of the panel has recently become moist from dew or rain, hence inspections are best made during dry weather and not too early in the day. The rating is poor if there are small wood checks in all parts of the panel, if some of the checks are conspicuous, or if cupping of the board has begun. Numerous conspicuous wood checks, marked cupping, or loosening at nail fastenings requires a rating of bad. Figures 4 and 5 show test panels illustrating typical conditions rated fair, poor, or bad in protection.

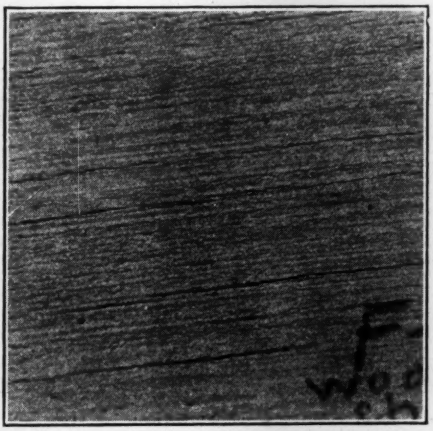


FIG. 4.—Small Wood Checks Appearing Where the Coating is Still Rated Good in Integrity (×2).

Such checks grow larger as time passes and finally become very conspicuous. If there are only a few checks like the ones shown, the panel is rated fair in protection, but if such checks are to be found in nearly all parts of the panel the rating is poor.

The ratings for integrity and protection do not depend upon the total area of bare wood or the total number of wood checks as much as they do upon the uniformity in distribution of the defects and their conspicuousness. Defining the ratings in this way gains the important advantage of minimizing the variations in coating behavior, caused by difference between boards in density, proportion of summerwood, width of annual rings, and angle at which the rings meet the surface (7).

In making ratings, the records of previous inspections are not consulted. Each inspection therefore represents an entirely independent judgment of the panel. The border line between ratings cannot be precise and some inconsistencies in the ratings for integrity and protection necessarily occur. It is considered highly advisable that experimenters be kept keenly aware of such limitations in subjective methods of judging results. After completing an inspection, however, it is well to consult the former records so that the inconsistencies will be detected in time to permit reconsideration of the test panel before further exposure has altered it. When the record form shown in Fig. 2 is used, the inspector will first set down his findings on a temporary form and then transfer them to the permanent form so that he can make his judgments without knowledge of the previous ones.

In any system of inspections depending upon subjective judgments, it is essential that the inspector avoid discussing the condition of test panels with anyone immediately before or during his examination because it then becomes difficult to pass judgment strictly independently. When more than one man takes part in an inspection, each one should record his decisions independently. They may then compare their data freely because each will be fully aware of any influence he permits the other to exert upon his own judgments. Without such precaution group inspections are less desirable than inspections for which one man is fully responsible.

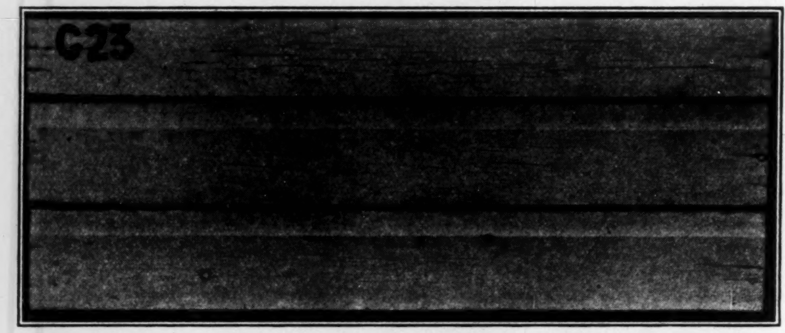


FIG. 5.—Conspicuous Wood Checks Showing that the Coating Has Been Bad in Protection for Some Time.

The coating is still rated good in integrity. On repainting these wood checks are not concealed satisfactorily.

The qualities and defects described as supplementary information may be rated if it seems desirable to do so. In the procedure of the Forest Products Laboratory, comparatively little effort has been made so far to define scales of ratings for this purpose. The new form of record, Fig. 2, provides for rating qualities good, fair, poor, or bad and defects none, trace, slight, marked, or very marked.

CONVERTING THE STATIC INTO A DYNAMIC RECORD

The method of converting the static into a dynamic record can be explained by specific example. The record of 12 inspections of panels Nos. 33 and 34 at Madison during a period of 56 months is summarized in Table II. Panel No. 33 was fair in integrity at 32 months and poor at the next inspection, 36 months. The useful life of the coating is therefore considered to be not greater than 36 months according to a rule that will be stated later. During the useful life of the coating its appearance was good for:

$$12 + (36 - 22) = 26 \text{ months}$$

and fair for: $22 - 12 = 10$ months.

TABLE II.—STATIC RECORD AT INSPECTIONS AT MADISON, WIS., ON TWO WHITE-FIR PANELS PAINTED WITH PAINT A CONVERTED INTO A DYNAMIC RECORD.

Age of Coating, months	Panel No. 33, Flat Grain			Panel No. 34, Edge Grain		
	Appearance	Integrity	Protection	Appearance	Integrity	Protection
4	Good	Good	Good	Good	Good	Good
10	Good	Good	Good	Good	Good	Good
12	Good	Good	Good	Good	Good	Good
15	Fair	Good	Good	Fair	Good	Good
22	Fair	Good	Poor	Fair	Good	Good
27	Good	Good	Poor	Good	Good	Fair
32	Good	Fair	Bad	Good	Fair	Fair
36	Good	Poor	Bad	Good	Fair	Poor
42	....	Bad	....	Good	Fair	Poor
46	....	....	....	Good	Poor	Bad
49	....	....	....	....	Poor	....
56	....	....	....	....	Bad	....

Similarly for panel No. 34 during 46 months useful life of the coating its appearance was good for

$$12 + (46 - 22) - 36 \text{ months}$$

and fair for: $22 - 12 - 10$ months.

In integrity, panel No. 33 was good for 27 months, fair or better for 32 months, and poor or better for 36 months, after which it was bad. Panel No. 34 was good for 27 months, fair or better for 42 months, poor or better for 46 months, after which it was bad.

It may be noted that, when a change in rating occurs between successive inspections, it is assumed arbitrarily to have taken place immediately after the earlier inspection. Sometimes the change is more than one step. Thus in panel No. 33 the rating for protection changed from good at 15 months to poor at 22 months. In this case it is assumed arbitrarily that the change from good to fair took place at the end of 15 months, and the change from fair to poor at the end of 19 months, which is about halfway between the inspections at 15 and 22 months. It is therefore concluded that, in protection, panel No. 33 was good for 15 months, fair or better for 19 months, poor or better for 27 months, and thereafter bad. Panel No. 34 was good for 22 months, fair or better for 32 months, poor or better until the integrity likewise became poor.

Figure 2 presents a dynamic record of the experiment in a very convenient way.

EXPRESSING THE DURABILITY OF THE COATING

The durability of a paint coating in practice depends both upon the behavior of the coating and upon the kind and degree of unserviceableness that moves the property owner to repaint it. Where poor appearance is the deciding factor, repainting will ordinarily be done before integrity or protection has deteriorated greatly (except under abnormal conditions of exposure that do not enter into test fence experiments). Often it becomes necessary to repaint for protection before it does for integrity, but most property owners do not recognize the necessity for repainting for protection. Everyone realizes that failure to maintain coating integrity is neglect. It therefore seems convenient to define a useful life, or durability, of the coating based upon consideration of integrity alone, to define a durability based upon protection as well as integrity, and to record the lowest rating for appearance and the age of the coating when it reached it.

The following arbitrary rules are adopted for defining the durability of the coating:

Rule 1.—The durability based upon integrity alone is the age of the coating when integrity is first rated poor.

Rule 2.—The durability, based upon protection as well as integrity, is the age of the coating when integrity is first rated poor if the rating for protection remains fair or better when integrity first becomes poor, but if not the durability is the age of the coating when protection was last rated fair preceding an inspection at which it was rated poor or bad.

In explanation of Rule 2 it should be pointed out that repainting restores a disintegrated coating more or less satisfactorily, but it does not heal conspicuous wood checks or straighten a cupped board. Maintenance of protection demands that repainting anticipate the development of weathering defects. It should be understood, of course, that the above rules are designed to aid the technologist in working up the data for his tests; they are not intended to guide the property owner in deciding when to repaint.

Applying the rules to the data of Table II the results of the tests cited may be expressed thus:

Panel 33.—Durability based on integrity only....................36 months
Durability based on protection also....................19 months
Worst appearance fair, reached within..................15 months

Panel 34.—Durability based on integrity only....................46 months
Durability based on protection also....................32 months
Worst appearance fair, reached within..................15 months

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PAINT FAILURE DIAGNOSIS

By Robert Job[1]

Synopsis

Paint failures resulting from various conditions have characteristic differences in appearance, so that usually it is possible definitely to fix responsibility for short life and likewise to determine what should be done to stop rusting and corrosion and avoid a repetition of the failure.

The general method which is followed in an investigation of this kind is described with typical examples taken from practice.

The painting of bridges and other structures exposed to weather is of the utmost importance on account of the heavy initial cost of such structures, together with the cost of maintenance and the difficulty in many cases of applying paint in exposed or inaccessible locations. With inferior materials—either pigment or vehicle—short and unsatisfactory protection naturally would be expected, and the characteristic appearance would generally be evident. Materials of excellent quality but not adapted or intended for that type of service would also fail and the cause could be determined by analysis or by the physical condition of the film. In some instances great precautions may have been taken to specify and to secure high-grade materials known from long experience to be well adapted to the conditions of service, careful instructions may have been given as to the preparation of the surface of the structure prior to painting, and the mechanical operation of painting may have received supposedly capable supervision, but none the less, the film upon an important steel structure may have failed within a year or two, involving inconvenience and unlooked-for, needless and unwarranted expense. In such a case, how can the causes of the failure be determined so definitely as to fix the responsibility where it properly belongs in order that steps may be taken to avoid the chance of a repetition?

Fortunately each type of failure has its own characteristic appearance which tells its own story and serves to indicate the cause, so that there is nothing mysterious in the diagnosis of a paint failure. An investigation of this kind involves a practical working knowledge of the properties of paint materials, both pigments and vehicles, likewise familiarity with the influence of different conditions of service upon the materials and also the ability to trace back the observed effect to the logical cause or causes, and thus detect the real reason for the failure.

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Let it be assumed by way of illustration that the paint upon a steel railroad bridge has failed after a life of less than two years and that rust spots have penetrated the film; also that parts of the structure are bare while other parts are of a streaky, unsightly appearance —in other words, that there has been an evident failure to protect. Regardless of the precise cause of the difficulty, the fact would remain that failure within the brief period of less than two years indicated unsatisfactory and expensive service, and many of us know of bridges which have remained in good condition without repainting over a period of eight or ten years and sometimes, under favorable conditions, for a considerably longer time.

The short life might indicate:

1. Failure properly to prepare the surface for painting. This would include painting over loosely adhering mill scale, rust, blisters, grease, etc., or painting over a damp or wet surface.

2. Improper application of the paint. Under this heading we would include:

(*a*) Failure to stir the paint and to keep it stirred so as to get good uniform consistency, and

(*b*) Failure to apply a good, even, well-brushed coating.

3. Bad paint, by which is meant paint either of inferior quality or of a composition designed and suitable for use under other conditions of service and not possessing the resistance to weather essential in a good bridge paint.

4. Special unfavorable conditions. Brine dripping from refrigerator cars is responsible for a heavy bill of expense which is not justified and which should be remedied. This action, though usually local, is none the less serious. Sand-blast from the exhaust from locomotives is also severe where little clearance is given. In such cases the cause would be evident and steps could be taken to remedy the conditions. Paint applied upon the under side of a bridge over water is frequently short-lived and ineffective in giving reasonable protection and the causes will be referred to below. Acid fumes from manufacturing plants sometimes cause rapid deterioration of a painted surface. Instances such as these are typical of special conditions which frequently result in failure and in these cases the preparation of the surface before painting, the quality of the paint itself or lack of skill

on the part of the painters may have had little or nothing whatever to do with the short life, but under even these unfavorable conditions it is quite possible that a much longer life might have been obtained from other coatings better adapted to that particular service.

Let us assume further that the ingredients of the paint were of good quality, but that through carelessness or neglect the paint was not thoroughly stirred and consequently was thin-bodied when applied. As a consequence the film would be deficient in pigment and would lack the capacity to give good protection against the weather; for linseed oil, as is well known, absorbs moisture and does not give good service unless reinforced by pigment. In a case of this kind, even within a year or so after application, the film would be likely to have become disintegrated and powdery and the portions of the film which remained in good condition in less exposed positions would, on analysis, be found deficient in pigment and in all probability far below the proportion called for in the specifications. Such a condition of the film would therefore be proof of careless or ineffective work on the part of the painters, as well as lack of proper oversight of their work—provided that the paint as received by them was of good standard quality.

Mention has been made of a "washed-out" mottled appearance, and a typical instance will point out our meaning. A steel highway bridge over a railroad yard had received three coats of paint. The first consisted of red lead of good standard quality, the second was a light gray mixture of white lead and zinc oxide colored with a small proportion of lamp black. The third or top coat was of essentially the same composition as the second but with a larger proportion of black, resulting in a slate gray. This structure, after exposure of less than two years, showed the characteristic faded and mottled appearance to which we have referred. Examination showed numerous spots where the third coat, although spread over the second coat, had not adhered, and the film of the third coat over such spots had worn away, exposing the light gray shade of the second coat and thus giving the faded and mottled appearance. The surface of these light-colored spots was smooth and often pear-shaped and it was evident that this portion of the third coat had been applied after a rain and while rain-drops still remained upon the surface of the structure. Bad work upon the part of the painters, and well covered until the tell-tale outline of the rain drops appeared after the disintegration of the third coat, giving silent testimony to slipshod, perfunctory work!

In connection with this bridge it should be noted that the choice of pigments, while excellent for general highway use, was unfortunate when applied upon a structure spanning a railroad yard and subject to sulfur fumes and moisture. Under such conditions chemical solvent action would be certain to result and the film would wear away after a far shorter life than should have been obtained with acid-resisting and less expensive pigments.

Turning again to the examination of our bridge, we have mentioned the appearance of rust spots and in some places lines of rust breaking through the paint. Close inspection at such places showed that the adjacent paint was in good condition with a tough, tenacious coating of red lead adhering closely to the steel, and the latter, on scraping away the red lead, was found bright and clean without a sign of rust and in perfect condition. This was conclusive evidence that the steel surface at such locations had been clean and properly prepared when painted and also that the paint was of good quality. The fact that rust spots had broken through the near-by portions of the paint was clear proof that the first coat of red lead applied at the mill had been painted over loose mill scale without even a reasonably effective wire-brushing. Here the fault rested with the mill and with those in charge of the painting in the mill. All of the subsequent cost of removing the rust, cleaning the surface and repainting, represented waste of time and money caused by evident lack of common-sense practice well known to every good painter. In order to "save the surface" we must first "clean the surface"! This latter term would be a good slogan for every painter, and if kept in mind and practiced, would avoid many a paint failure.

Let us next examine some of the blisters which appeared upon the bridge. Careful cutting with a sharp knife showed that the film of paint covering the blisters was tough, flexible and strong, and also that all three coats of the paint had been forced up from the steel by formation of rust. Some of the blisters were 2 in. in diameter and $\frac{1}{2}$ in. high. Further examination showed that loose mill scale was responsible for the condition. In other words, expansion and contraction of the steel—in the hot sun, and during cool nights—had loosened the scale, breaking the paint film and permitting entrance of water to the steel with the resultant rusting. All around the blisters the film was in excellent condition without a sign of rust. Careless mill practice, as noted above.

On another bridge it was found that the painters, evidently ambitious to make good headway, had painted over blisters and rust, disregarding the elementary rule that the surface must be clean and dry before the paint is applied. A condition of this type is readily detected by the method described above, and of course indicates lack of knowledge or disregard of instructions on the part of the painter, and lack of effective oversight on the part of the foreman.

Let us now turn briefly to the examination of "bad paint," including paint of inferior quality and also composition unsuited to the conditions of service under which it was to be used. A good illustration of this latter type was found on some of the wooden panels upon the first Atlantic City test fence,[1] and it will be recalled that in several instances the films had entirely disappeared within a year from time of exposure. Linseed oil was the vehicle and the pigments, though excellent for other purposes, were not resistant to weather. In such cases analysis of the film would give a clue as to the cause of failure, but the film itself would show the well-known characteristic disintegrated and brittle appearance, indicating clearly that "the life had gone."

Now and then an inferior non-drying oil is used in the vehicle, and in the less exposed positions the film may remain in a sticky, dust-catching condition for a considerable time, though in neighboring, more exposed positions, the breaking down of the film may be very marked and easily identified.

Sometimes the paint has been deliberately cheapened by the addition of an excessive proportion of "mineral spirits" or painters' benzine; consequently the bonding power of the vehicle is deficient and a "flat" surface, without gloss, is obtained with quicker powdering of the surface and more rapid mechanical wear due to weathering than should have occurred. Excess of water in an outside paint would have a somewhat similar effect on weathering, and we have in mind one highly recommended outside paint which contained over 40 per cent of water in an emulsified condition, "added to improve the film." On weathering, the film became "flat" and powdery. The water of course evaporated and the film was obviously deficient in bonding power with relatively a high proportion of pigment.

Mention has been made of failure of paint on the under side of a bridge over water. Under these conditions it is frequently difficult to get a dry, clean surface, and all too often the paint is brushed upon the steel while the latter is damp or wet. Under such conditions the film does not adhere and rust builds up quickly underneath the coating. Unluckily for the bridge, the color of the paint is retained for a considerable time until the rust breaks through the film so that the true corroded condition of the steel is detected only by a close and careful examination. In such a case the film of the paint would be tough, but a mass of rust would be found beneath the coating and it would be evident that there never had been a bond between paint and steel.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. X, p. 107 (1910).

The vital influence of the condition of the surface upon durability was shown upon our typical bridge in a remarkably interesting and striking manner. The hand railing along the outside of the bridge was constructed of cast-iron posts about ten feet apart, while 2-in. steel pipes extended horizontally between the posts near the top and near the bottom of the latter. Steel rods $\frac{3}{4}$ in. square were spaced vertically about 6 in. apart and set into the upper and lower pipes. All of this work had been painted with the same paints as the main body of the bridge. After two years' service the coatings upon the cast-iron posts were in excellent condition without a sign of rust and undoubtedly would give excellent protection for many years. The steel pipe and rods on the other hand, painted at the same time and with the same materials, were entirely bare and badly rusted in locations where both posts and steel work had been exposed to smoke from locomotives. This extreme difference in service within a couple of years is, we think, fully accounted for by the condition of the surfaces to which the paint was applied. The steel parts, both pipe and rods, were undoubtedly covered with the usual smooth mill scale, whereas the cast-iron posts had the roughened surface characteristic of cast iron with very little scale, and expansion and contraction with such a surface evidently had no influence upon the integrity of the coating and the acid fumes were kept from the metal. In the case of the steel, the smooth scale evidently became loosened by the action of heat and cold, the coating of paint then became broken and moisture and fumes penetrated to the steel, causing quick corrosive action which speedily resulted in the sloughing off of the paint. Sand blasting of the steel in such an exposed location immediately prior to the painting in all probability would have avoided the trouble.

In the description which we have given of types of failure of paints, we have touched upon only a few of the more glaring conditions which are likely to occur in service. They will serve, however, to illustrate the general mode of examination.

In the case of the typical bridge to which we have referred the evidence was clear-cut and unmistakable, as follows:

1. The first coat, red lead, applied in the mill was of good quality, but in some places it had been spread over loosely adhering mill scale which should have been removed prior to the painting.

2. The second coat—the first field coat—was of good quality and the application generally was satisfactory.

3. The top coat also was of good quality but was applied when a part of the structure was wet, and consequently failure of the third coat occurred at such places. In addition, the character of the brush marks, particularly at and around rivets, showed clearly that this coat had not been evenly applied and that it had not been properly brushed.

The general conclusions, therefore, were:

1. Lack of proper preparation of the surface of the steel in the mill prior to application of the first coat.

2. Lack of effective oversight of the work of the painters at the bridge.

3. The paint comprising each coat was of good standard quality but the composition of the pigment in the second and third coats was not well adapted to exposure in a railroad yard, and much longer life would have been obtained under such conditions by use in the last two coats of pigment having greater resistance to acid fumes, as well as lower initial cost.

In an investigation to determine the cause of failure of a protective coating, one must not jump to conclusions. The evidence must be taken carefully and impartially and the reasoning from result to cause must be followed backward, step by step, to the logical conclusion. The examination should, if possible, be conducted in the presence of the engineer or his representative so that each condition would be seen, discussed and thoroughly understood. It is easy to follow the course of least resistance and to say "the paint has failed" and then to repaint with some other material, but such a course is not logical, it does not tend toward better dividends from the expenditure, and the final result is apt to be a disappointment to the engineer. In any type of work it is far better to determine the real cause or causes of the difficulty and then to direct one's energies to those particular features.

Having thus definitely established the conditions which resulted in the failure, it should be possible to fix upon the proper remedy. In one case this might involve entire rearrangement of the methods for preparation of the surface prior to the application of the first coat of paint; in another case the number of coatings or the composition might require change, and in still another, methods for the careful supervision of the work of the painting might be found essential. In any event, when once the real underlying causes were fully established, half of the problem would be solved, and then it would be simply a case for active and well-directed effort against a known enemy.

HIDING POWER MEASUREMENTS IN THEORY AND APPLICATION

BY A. H. PFUND[1]

SYNOPSIS

Tentative definitions for (1) hiding, (2) hiding power of a paint and (3) hiding power of a pigment are presented. A new "Black-and-White" cryptometer, based on the above definitions, is described and the usefulness of this instrument for measuring the wet hiding powers for all types and colors of coatings is demonstrated.

A precision cryptometer, involving the use of a photoelectric cell in place of the human eye, has been developed. This device, which is extremely sensitive and free from the subjective errors of the human eye, yields precision results of hiding power.

In the devising of any test, two necessary steps must be taken: (1) a rigorous definition of the quantity to be measured must be formulated, and (2) an instrument or a method, embodying the established definition, must be developed for measuring the quantity in question. The quantity to be dealt with here is "hiding power," that property of a coating which enables it to obliterate a contrasty background.

The following definitions are presented:

DEFINITIONS

Hiding.—The coating is to be applied uniformly over an impervious, flat background which is in part black (coefficient of diffuse reflection 8 per cent or less) and in part white (coefficient of diffuse reflection 80 per cent ± 2 per cent). When the ratio of the brightness of the coating overlying the respective black and white areas is 98 per cent, hiding is defined as being "complete."

Hiding Power of a Paint.—That quantity of a paint which must be applied to a given area of black-and-white background to bring about complete hiding (as defined previously). It shall be specified whether measurements of hiding are carried out on "wet" or "dry" paint films.

Hiding Power of a Pigment.—A value numerically equal to the number of unit areas which a unit mass of dry pigment, after having been incorporated with a specified vehicle in a specified pigment-vehicle ratio, will "hide." Wetness or dryness of the film and its brightness (coefficient of diffuse reflection) shall be specified also.

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It is obvious that these definitions are but an elaboration of the long established "paint-out" test. It is furthermore evident that any acceptable method of measuring hiding power must involve the procedure of applying a coating over a black-and-white background to complete hiding. To be specific, this simply means that if the tinting-strength test be used as a measure of the hiding power of a pigment, it is necessary to establish for each individual case that the findings agree with those obtained by means of a method conforming to the accepted definitions. In case of disagreement, the results obtained by the tinting-strength method must, of necessity, be rejected.

Perhaps the only point calling for comment in the definition of hiding is the one which defines hiding as being complete at a 98-per-cent brightness ratio. This is nothing more nor less than the well-known Weber-Fechner law, according to which the least perceptible increment of light-intensity (for moderate illumination) is about 2 per cent. While those endowed with keen vision can recognize intensity differences of less than 2 per cent, particularly when large areas are viewed with both eyes, there are others who require a greater difference. The 2-per-cent difference or the 98-per-cent brightness ratio is therefore considered a fair average. What is of greatest importance, however, is that once having fixed the 98-per-cent point "by-law" it becomes possible to develop a precision method for determining complete hiding.

The combined definitions for hiding and for the hiding power of a paint are already on record in the minutes of the February 7, 1930, meeting of Subcommittee VIII on Methods of Analysis of Paint Materials of the Society's Committee D-1 on Preservative Coatings for Structural Materials. A definition of the hiding power of a pigment has not, as yet, been considered. Measurements of this type are in the nature of a prognosis, being carried out to predict the hiding qualities of a pigment when forming part of a paint. In view of the large differences in oil absorption, brightness, dilution effects[1] and changes in hiding power on drying, it is obvious that specific and different recommendations ought to be made for each type of pigment and vehicle. Since dirt or other dark, contaminating material increases the hiding power of a pigment it will be necessary, for purposes of intercomparison, to tabulate also hiding powers at equal brightness. This entire matter, which is of paramount importance to the pigment manufacturer, demands further careful consideration.

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[1] The dilution effect is observed when hiding power measurements are carried out on mixtures whose pigment-vehicle ratio is varied through wide limits. It is found that unit mass of the pigment will hide increasingly greater areas as the pigment-vehicle ratio is decreased.

THE "BLACK-AND-WHITE" CRYPTOMETER

It is left for others to take up a critical discussion of the various methods of measuring hiding power. My purpose is, primarily, to discuss the application of the cryptometer to the problem under discussion. In its original design[1] the cryptometer conformed strictly to the definition of hiding power then formulated. Since, however, a new definition of hiding power is being considered it seems expedient to describe a new "Black-and-White" cryptometer which conforms to the latest definition and to compare the results thus obtained with those found with the older (regular) cryptometer.

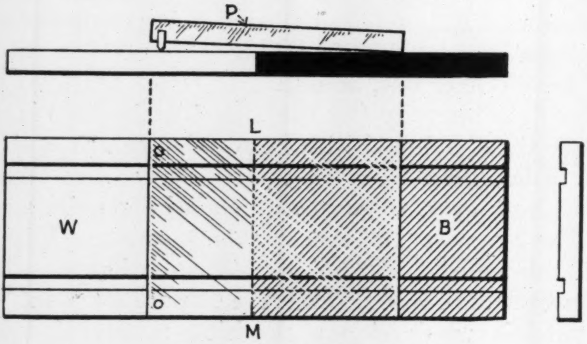

FIG. 1.—Black-and-White Cryptometer.

The construction of the new instrument is shown in Fig. 1, from which it is seen that the base consists of pieces of black, *B*, and white, *W*, glass, fused together along the line *LM*. The usual longitudinal grooves are retained, but the deep central well is eliminated. As formerly, the top plate, *P*, of clear glass imprisons a film of wet paint whose thickness is varied until the line of demarcation *LM* has disappeared. The reflection coefficients for the white and black parts of the base plate are 80.5 and less than 5 per cent, respectively, thus conforming to the accepted definition. Correct measurements for a wet paint are obtained by taking readings for disappearance and appearance of the line of demarcation, first for the lower plate in the position shown in Fig. 1, and then with the relative positions of the two fields reversed.

In the course of the series of tests carried out in cooperation with Subcommittee VIII, occasion was found to measure the hiding powers of a series of paints with both types of cryptometer. The results are shown in the following table:

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[1] A. H. Pfund, *Journal*, Franklin Inst., November, 1919, p. 675; July, 1923, p. 77.

			HIDING POWER, SQ. FT. PER GAL.	
PAINT	PIGMENT, PER CENT	VEHICLE, PER CENT	REGULAR CRYPTOMETER	BLACK-AND-WHITE CRYPTOMETER
White Lead	80.7	19.3	300	290
Zinc Oxide	64.7	35.3	232	219
Lithopone	69.5	30.5	292	270
Titanox	70.6	29.4	280	273
Zinc Sulfide	66.5	33.5	430	410
Titanium Oxide	66.0	34.0	560	563

From these data it is clear that the two types of cryptometer yield the same results for white paints, within experimental error. The reason for this is pointed out in the paper presented at this meeting by G. F. A. Stutz, Jr., and G. S. Haslam,[1] who show that for white paints whose brightness is in excess of 70 per cent, the regular cryptometer yields essentially the same results for wet paints as does the refined paint-out test.

It is to be pointed out that, in addition to yielding results which are in conformity with the accepted definition of hiding power, the black and white cryptometer may be used for paints of all colors. To gain some idea of the hiding powers of commercial colored paints and lacquers, some samples prepared by reputable manufacturers were purchased in the open market. These samples were first stirred and shaken to render them uniform and were then tested. The results are as follows:

PAINT	COLOR	HIDING POWER, SQ. FT. PER GAL.
Exterior House Paint	White	257
Exterior House Paint	Old Ivory	435
Exterior House Paint	Pure Blue	1050
Exterior House Paint	French Green	1400
Automobile Color	Vermilion	470
Lacquer	White	190
Lacquer	Buff	404
Interior Enamel	White	126

We are here not concerned with the great range in hiding power shown by these samples: the fact remains that colored coatings are readily susceptible of measurement by means of the new cryptometer.

Mention is to be made of the fact that as a result of a number of carefully executed paint-out tests[2] it was found that if such vehicles as oils or varnishes be used, the difference between wet and dry hiding powers of white coatings is small. It is therefore concluded that for the vehicles mentioned the cryptometer yields approximately correct results also for the dry paint.

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[1] "A Discussion of Hiding Power and Its Measurement," see p. 884.

[2] A. H. Pfund, *Journal*, Franklin Inst., April, 1921, p. 522.

PRECISION CRYPTOMETER

Perhaps the greatest weakness of the paint-out test and of the cryptometer lies in the indefiniteness of the end point. While skilled operators are capable of obtaining consistent results whose average deviation from the mean is about 5 per cent, a higher degree of accuracy, free from the personal equation, is required before it may be said that a precision method is available. An attempt to meet this situation has been made by taking advantage of the tremendous sensitivity of the photo-electric cell (potassium hydride). If the color-sensitivity of such a cell be corrected by means of suitable filters to simulate the response curve of the average human eye, it will be possible to replace the latter (with its contrast sensitivity of 2 per cent) by an instrument whose contrast sensitivity can be made to exceed that of the eye a hundred-fold or more. While application of the photo-electric cell to the cryptometer is here presented, the same mode of procedure may be followed in carrying out precision paint-out tests.

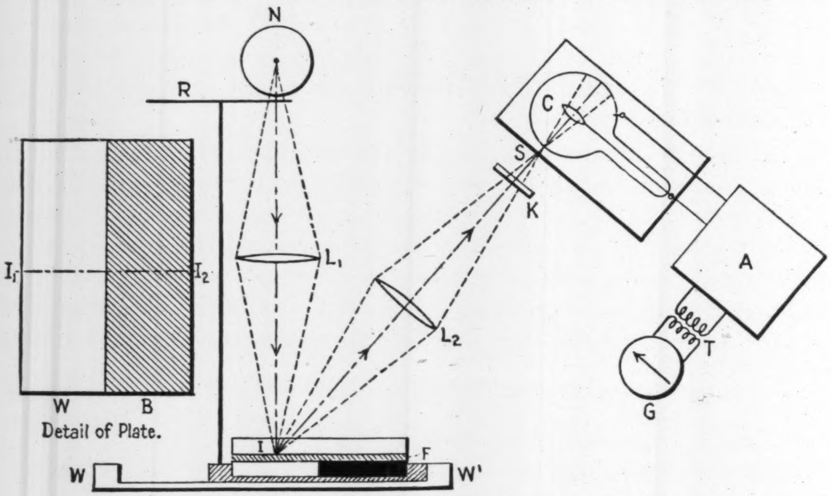

FIG. 2.—Precision Cryptometer.

The essentials of the apparatus are shown in Fig. 2. The base plate consists of black and white portions, *B* and *W*, whose line of separation runs lengthwise. The clear top plate is as large as the base plate. For general purposes the wedge angle between the top and base plate is made about one-half that of the usual cryptometer (wedge angle, 0.007 deg.). It is not necessary to fuse the black and white plates together, but it is essential that their upper surfaces be co-planar. The general mode of procedure for making measurements is, briefly, this: if we reduce the intensity of the light reflected from the paint film F, overlying the white glass by 2 per cent but do not reduce the intensity from the paint film overlying the black glass, then, somewhere along the length of the wedge of paint, these two intensities are just equal. In Fig. 2, N is a ribbon-filament tungsten lamp. An image of the filament is projected on the paint film at I. By means of the lens L_2 an image of I is formed on a slit S which allows the light to enter a potassium-hydride photo-electric cell C. In front of this cell is placed a color screen K of such a character as to make the spectral sensitivity of the photo-electric cell identical with that of the average normal human eye. The terminals of the photo-cell are connected to an amplifier, A, which is not of the bridge type, but rather of the type which allows a relatively large plate current to flow in the last stage of amplification. This current is passed through the primary of the transformer T, while the secondary is connected to a ballistic galvanometer G having a complete period of about 10 seconds. To begin with, the image is formed at I_1 with the rotating sector (spokes) R in motion, thus cutting down the light intensity by 2 per cent. Suddenly the entire cryptometer is moved to the left, thus removing the rotating sector from the light path and allowing the image to be formed at I_2. If the intensities of I_1 and I_2 are different, there will be a change in the current flowing through the primary of the transformer and, as a result, the galvanometer will show a deflection. It is than merely necessary to slide the entire cryptometer longitudinally in the ways W-W' and to repeat the previous operation until a position is found which occasions zero galvanometer deflection as the image is shifted from I_1 to I_2. A scale suitably attached to the cryptometer makes it possible to determine the film thickness at complete hiding.

A detailed description of this apparatus is reserved for a later date. Suffice it to say that the preliminary results already obtained show that the 98-per-cent point of complete hiding may be established definitely at 98 per cent ± 0.04 per cent. While the apparatus may appear complicated, the taking of readings is extremely simple. There is no sliding of the top plate relative to the base plate, no visual estimate of disappearance of a fading line of demarcation; it is merely necessary to find the position of the cryptometer such that no galvanometer deflection results when the filament image is shifted from the white field to the black.

Acknowledgment.—In conclusion the author desires to express his appreciation of help given in this work by D. L. Gamble.

[For Discussion on Hiding Power of Paints, see page 903.—ED.]

A DISCUSSION OF HIDING POWER AND ITS MEASUREMENT

By G. F. A. Stutz, Jr.,[1] and G. S. Haslam[1]

Synopsis

This discussion is based on results obtained by several new developments in the measurement of hiding power. An effort is made to point out the value of the several tests now in use and the interpretation that is to be put on them.

The relationships existing between hiding power and brightness, and film thickness and brightness are developed. The subject is presented in light of the findings of Subcommittee VIII on Methods of Analysis of Paint Materials of the Society's Committee D-1 on Preservative Coatings for Structural Materials, and uses the tentative definition adopted by them as a working basis.

One of the greatest requirements placed upon a white pigment or paint is its ability to hide or cover the background upon which it is placed. From a practical standpoint the white paint must be able to brighten a dark surface and to obliterate any contrast which may exist on that surface. The measurement of these properties is difficult and somewhat complicated. This fact has forced paint and pigment technologists to resort to tests measuring other properties of the pigment or paint similar to its hiding power. Measurements of tinting strength, particle size, and opacity to transmitted light have been used in an effort to obtain a test which would measure hiding power indirectly. Foremost among these methods is the so-called tinting strength test which, in the case of a white pigment, measures its ability to withstand coloration by a small amount of a colored pigment. The most obvious discrepancy between the tinting strength test and hiding power is that the contamination of a white pigment with a colored pigment or dirt causes a decrease in brightness, resulting in an increase in its hiding power and a decrease in its tinting strength. The particle size of a pigment often parallels its hiding power, but here it is possible for differences in flocculation effects to cause quite serious reversals in hiding power so that particle size as a measure of hiding power becomes inaccurate. The opacity of the pigment or paint to transmitted light is a third property that somewhat parallels hiding power. It has been our experience using the Stutz-Pfund Turbidimeter[2] that the pigment giving the maximum opacity to transmitted light does not necessarily have the best hiding power. Extremely fine colloidal pigments show a much higher hiding power than their opacity measurement would indicate. In all of these tests, the concentrations of pigment and vehicle vary, so that the test is rarely, if ever, made at painting consistency. Since the pigment-vehicle concentration has been found to markedly affect such determinations, a serious error may be introduced.

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[1] Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] *Industrial and Engineering Chemistry*, Vol. 19, p. 51 (1927).

We may sum up the situation by saying that while the direct measurement of the hiding power of a white pigment is extremely difficult, the measurement of other properties which has been resorted to fails to measure hiding power with any degree of accuracy. It becomes necessary, therefore, to develop accurate means of measuring the hiding power of a pigment directly. We propose to discuss this direct measurement of the hiding power of a pigment or paint and some of the factors which are involved.

The tentative definition for hiding power adopted by Subcommittee VIII on Methods of Analysis of Paint Materials of the Society's Committee D-1 on Preservative Coatings for Structural Materials is used as a working basis. This definition reads:

> The hiding power of a paint is measured by that area of an impervious black-and-white background, the white portion of which has a brightness of 80 ± 2 per cent and the black having less than 8 per cent brightness, which can be covered by a stated quantity of the paint so as to bring the black background to within 98 per cent of that over the white background, and shall be specified as wet or dry.

In this discussion, this definition will be further amplified to specify the brightness of the resulting film if a coat of infinite thickness is applied.

The time-honored test for hiding power is the so-called paint-out test where a weighed amount of paint is applied to a white board marked with black stripes or irregular figures. Successive coats of paint are applied and allowed to dry until the black markings are no longer visible or are only very faintly visible. Such a test is quite unsatisfactory in that it is long, tedious. and quite inaccurate, an error of 25 per cent being possible.

The principle underlying the paint-out test is correct. Such a test measures hiding power as defined above. To improve its accuracy and to make it more exactly conform with the above definition, it is necessary to effect the following qualifications:

1. The paint must be more uniformly applied than can be done by brushing.

2. It must be possible to increase or decrease the amount of paint applied by very small amounts, much less than that of a normal coat of paint.

3. The white and black portions of the background must be made to meet the figures given in the definition.

4. Some exact method must be used to determine the point at which the brightness over the black background is within 98 per cent of that over the white background.

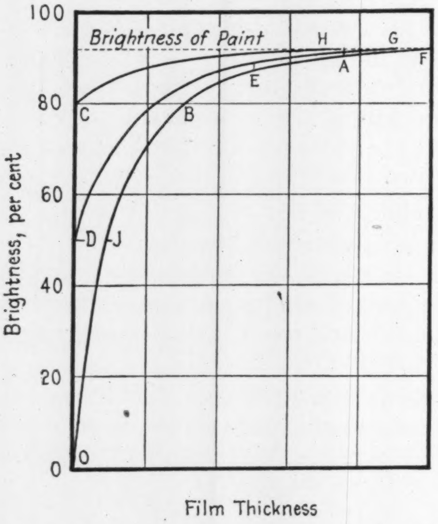

FIG. 1.—Relation of Brightness to Film Thickness.

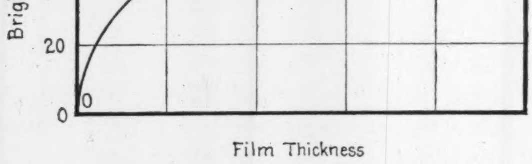

FIG. 2.—Relation of Brightness to Film Thickness.

5. It is desirable to be able to make the measurement on both the wet and the dry film.

When white paint is applied over a background having a brightness other than that of the paint, a change in brightness is effected that continues with increasing film thickness until the brightness of the paint is reached. The performance of a paint when applied in this way over a background is illustrated in the curves in Figs. 1 and 2. These curves are similar to those determined by Gamble and Pfund[1] and Haslam.[2] Figure 1 illustrates the case where the paint applied is considerably brighter than either the white or black background specified in the definition, that is, 80 per cent for the white and less than 8 per cent for the black. Curve *OF* indicates the increase in brightness with increasing film thickness over a black background of zero per cent brightness. Curve *DG* indicates the increase in brightness over a background of 50 per cent brightness, and is identical in shape with curve *JF*. Curve *CH* shows the increase over a background of 80 per cent brightness, and is identical in shape with curve *BF*. The vertical distance between any two of these curves may be considered as a measure of the contrast remaining when a given film of paint is applied, and when that distance is equal to 2 per cent the contrast is no longer detectable with the eye, which is the point of complete hiding according to the definition. It will be noticed that the vertical distance between curves *CH* and *OF* is constantly diminishing and becomes 2 per cent at the film thickness designated by *A*. For any brightness of the white background greater than 80 per cent, it is obvious that the point of complete hiding will not be changed. Considering the curves *DG* and *OF*, the vertical distance between these curves becomes 2 per cent at the point *E* which is at a film thickness less than *A*, indicating that this paint has a better hiding power over a background of 50 per cent – 0 per cent than it does over one of 80 per cent – 0 per cent. Examination of a large number of such curves for different pigments indicates that there is no appreciable increase in the hiding power of a bright white paint as the brightness of the white background is decreased until that brightness approaches the region of 60 per cent.

Figure 2 illustrates the opposite case where the white background is considerably brighter than the paint to be measured. In this case, curve *OA* represents the performance of a paint of approximately 65 per cent brightness over a black background and *O'E* that over a background of 80 per cent brightness. Point *A* is the film thickness to give complete hiding if the white background has a brightness of approximately 65 per cent. Since the change in brightness over the 80 per cent background takes place much more rapidly than the change in brightness over the black background, the hiding power of this paint is still measured by the thickness at the point *A*. Therefore, the hiding power of this paint is the same in both the case where the white background has a brightness of 65 per cent, and in the case where the white background has a brightness of 80 per cent.

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[1] *Industrial and Engineering Chemistry* (Analytical Edition), Vol. 2, p. 63 (1930).

[2] *Ibid.*, p. 69.

However, if the white background is considerably brighter than the paint, as illustrated in Fig. 3, the hiding power is measured by the thickness at point *E* rather than at point *A*; that is, the hiding power is decreased. It is, therefore, evident that in the case of any one paint, using the white background of 80 per cent specified in our definition, the points *A* and *E* practically coincide as the brightness of the paint is decreased until a certain critical brightness is reached. For brightnesses of the paint lower than this critical value, the points *A* and *E* no longer coincide. This critical value will vary somewhat for different pigments.

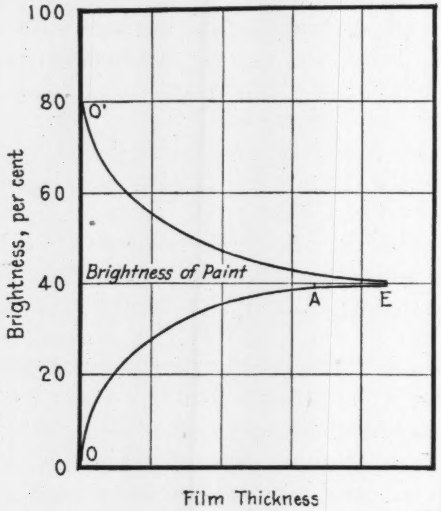

FIG. 3.—Relation of Brightness to Film Thickness.

Such an analysis of the brightness-thickness curves of paints indicates that when the black-and-white backgrounds specified in our definition are used, the hiding power of a paint that is greater than 70 per cent in brightness will be practically the same whether it is measured in such a way as to determine the point *E* or to determine the point *A*.

The Pfund cryptometer in the case of a wet paint accurately measures the point *A*. The operation of this instrument is simple and the instrument itself has no complicating features. The only requirement is that the operator be thoroughly trained in the use of the instrument and be as unprejudiced as possible. The Pfund cryptometer has the one disadvantage, that it can measure hiding power of wet paints only. Keeping in mind the requirements set forth to improve the paint-out test, we find that the Pfund cryptometer meets these requirements admirably with the limitation that wet hiding power only is measured and that paints greater than 70 per cent in brightness only are measured.

The instrument designed by Bruce[1] in which the relative brightness of the film of paint over a black and over a white background is measured, incorporates all of the requirements of our improved paint-out test. Its only disadvantage lies in the fact that, as pointed out by Gamble and Pfund,[2] the brightness-thickness curve *OA* never follows any exact mathematical relationship but is different for every pigment. The Bruce method, as outlined, extrapolates to the point *E* using an assumed mathematical expression for the curve. It may, therefore, be inaccurate in item No. 4 of the limitations placed on the paint-out test; that is, it is inaccurate in its measurement of the point in which the brightness over the black background is 98 per cent of the brightness over the white background. This objection would be overcome if the measurements were made at a thickness of film which gives approximately complete hiding. Limitations of the apparatus, particularly the measurement of film thickness, place a rather serious restriction on the Bruce method.

A more recent method in which the brightness-thickness curve is determined has been described by one of the authors[3] in which the curve *OA* is accurately determined throughout its entire length by means of a special spinning device for obtaining uniform films over a black glass, the thickness of which is determined by weighing and by use of the Pfund colorimeter to measure accurately the brightness. The technique described in the original paper has been still further modified so that instead of a plain black background a black-and-white background is used and the point of complete or nearly complete hiding is judged by the eye.[4] The so-called spinning film method meets all of the requirements which we place on an improved paint-out test.

In its modified form, this test is somewhat more simple and rapid than in its original form, though its accuracy is slightly decreased, since the eye is substituted for the photometer in the determination of the point of complete hiding.

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[1] *Technologic Paper No. 306*, U. S. Bureau of Standards.

[2] *Industrial and Engineering Chemistry* (Analytical Edition), Vol. 2, p. 63 (1930).

[3] *Ibid.*, p. 69.

[4] A complete description of this modified method is given in a paper presented before the Paint and Varnish Division, Am. Chemical Soc., April, 1930, by G. S. Haslam entitled "A Modification of the Spinning Film Hiding Power Method."

Gardner[1] has recently described a modified paint-out test that is quite simple and rapid.[2] Using as a background a checkerboard of black-and-white linoleum which does not meet the brightness requirement of our hiding power definition he has obtained results that parallel but do not equal the cryptometer values. With the selection of the proper background, it is anticipated that the results to be obtained will approximate the cryptometer values. Since the Gardner test is only a very slight modification of the brush-out method, it suffers from such qualifications as lack of uniformity of the film, due to its application by brushing, and inaccuracy in determining the point of complete hiding.

Pfund has described a modification of the cryptometer in which a white glass and a black glass form the background to be hidden. With such an instrument the range of the cryptometer is extended to cover those paints below approximately 70 per cent in brightness so that the hiding power of any wet paint can be measured and will conform to our definition.

The methods of measuring hiding power which have been discussed and which conform to the tentative definition of hiding power, previously quoted, may be evaluated as follows:

1. The Bruce method if modified to experimentally determine the thickness for complete hiding will be a satisfactory method for determining hiding power. Its accuracy is somewhat impaired by the thickness determinations, and a complicated and expensive apparatus prevents universal application of the test.

2. The Haslam spinning film method, as originally outlined, will accurately determine hiding power and is fairly rapid. However, it requires some expensive equipment.

3. The modified Haslam spinning film method is a more rapid and perhaps a slightly less accurate method but does not require any complicated or costly equipment.

4. The modified paint-out test of Gardner, offers a possibly less accurate but more simple and inexpensive method of obtaining hiding power of wet paints.

5. The Pfund cryptometer is most satisfactory for wet paints greater than 70 per cent in brightness. It is most simple and rapid for an accurate determination of wet hiding power.

6. The Pfund black-and-white cryptometer gives an accurate measure of the wet hiding power of a paint of any brightness.

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[1] *Circular No. 362*, Educational Bureau, Am. Paint and Varnish Mfrs. Assn.

[2] See paper by H. A. Gardner, G. G. Sward and S. A. Levy on "A Practical Brush-Out Test for Hiding Power of Paints," see p. 891.

[For Discusssion on Hiding Power of Paints, see page 903.—ED.]

A PRACTICAL BRUSH-OUT TEST FOR HIDING POWER OF PAINTS

BY H. A. GARDNER,[1] G. G. SWARD[1] AND S. A. LEVY[1]

SYNOPSIS

This paper deals with a practical method of determining hiding power by actually brushing out a paint upon a surface of checkerboard linoleum made up of black and white blocks. The results obtained by this method are compared with results obtained by the Pfund cryptometer, and it is found that the brush-out method gives higher results. The results, however, retain the same order of magnitude.

INTRODUCTION

It has been found by experiment that the Pfund cryptometer will give quite satisfactory results when in the hands of an operator skilled in its manipulation. Usually it does not give accurate results when used by a factory worker who is not technically trained.

A search has therefore been made for a practical hiding-power test that could be used by the factory worker as well as by the technical man. A number of methods in use throughout the industry were tried, in an effort to find one which would be satisfactory. Brush-out tests were made upon various designs of oilcloth; printed gray blocks of varying brightness; numerous painted designs upon plain glass; white and black plate glass; paper, wood and metal; and upon designs developed on photographic paper. Several light transmission methods were also tested. Difficulty in duplicating the background, elevations between the black and white areas, poor surfaces for brushing, measurement of opacity instead of hiding power, and entrance of light between the paint film and the background, were among the difficulties experienced. The method described below was then developed.[2]

METHOD

A piece of checkerboard linoleum 24 in. square containing 4-in. black and white blocks, as shown in Fig. 1, was experimented with and after many brush-out determinations by both technical and non-technical men, it was found that results could be obtained which checked quite closely. It was decided therefore to adopt this as a standard upon which to base further work.

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[1] Chemist, The Institute of Paint and Varnish Research, Washington, D. C.

[2] For a more complete discussion of the method and test results see *Circular 362*, Scientific Section, Am. Paint and Varnish Mfrs. Assn.

The brightnesses of the black and white blocks were approximately 10 and 60 per cent, respectively. An effort was made to secure linoleum on which the black would have a brightness below 8 per cent and the white around 80 per cent.[1] This has not been successful.

In conducting the test, the linoleum is first well rubbed with oil to fill the pores, the excess oil being thoroughly rubbed off. The can of paint and the brush are weighed to ± 0.5 g. A brushful of paint is spotted on each square. It is then brushed out, cross-brushed, and laid off. This process is repeated, if necessary, until the contrast is obliterated. The can and brush are then re-weighed and the results expressed in square feet per pound of pigment, square feet per gallon of paint, or in any other desired units. The paint is then scraped off and the linoleum wiped clean to make the surface ready for the next test. This method provides a base of comparatively low cost, which will last a long time. It possesses the advantage that the non-technical operator can visualize the results.

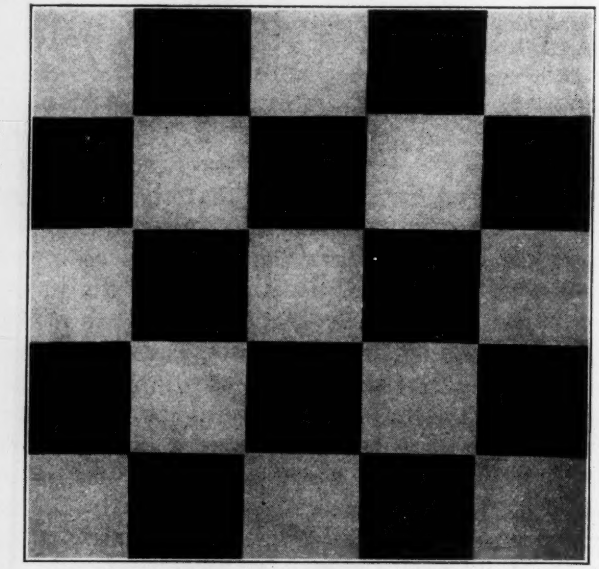

FIG. 1.—View of Checkerboard Linoleum Developed for the Brush-out Tests.

The brightness of the black and white blocks are 7.6 and 68.6 per cent, respectively.

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[1] Armstrong Cork Co. kindly made up blocks at our request.

TABLE I.—PRECISION OF LINOLEUM BRUSH-OUT METHOD FOR DETERMINING HIDING POWER.

	Paint Applied to 20 by 24-in. Area, g.										
	Titanium Oxide	Zinc Sulfide	Titanox "C"	Zinc Oxide	High Strength Lithopone	Titanox "B"	Antimony Oxide	Lithopone	Zinc Oxide 35 per cent Leaded	Basic Lead Carbonate	Basic Lead Sulfate
Operator 1	41	49	61	90	69	69	70	72	88	90	146
	48	43	61	98	62	68	77	74	87	..	156
	47	..	..	..	62	..	..	..	..	..	...
	..	..	..	..	62	..	..	..	..	..	...
Operator 2	41	46	61	90	63	70	78	71	86	75	129
	42	56	62	88	63	69	75	73	84	..	131
	..	..	..	..	..	..	76	74	83	..	144
	..	..	..	..	..	..	..	74	..	..	...
Operator 3 including five operators available at different times	40	44	60	..	51	59	..	76	..	85	125
	51	..	..	..	66	60	..	74	..	70	115
	..	..	..	..	65	60	..	72	..	..	...
	..	..	..	..	..	60	..	..	..	..	...
	..	..	..	..	..	61	..	..	..	..	...
	..	..	..	..	..	66	..	..	..	..	...
	..	..	..	..	..	67	..	..	..	..	...
	..	..	..	..	..	70	..	..	..	..	...
Average	43	48	61	92	63	66	75	73	86	83	135

TABLE II.—HIDING POWER OF PAINTS OF EQUAL MOBILITY.

Pigment	Composition		Pigment per Gallon of Paint, lb.	Cryptometer		Linoleum Brush-out Method	
	Pigment, per cent	Oil, per cent		Fresh Paint, sq. ft. per lb. of Pigment	Aged 2 Weeks, sq. ft. per lb. of Pigment	Fresh Paint, sq. ft. per lb. of Pigment	Aged 2 Weeks, sq. ft. per lb. of Pigment
Titanium Oxide	56.5	43.5	7.8	62.6	51.2	68.9	58.7
Zinc Sulfide	68.2	31.8	11.4	30.7	26.5	43.0	42.8
Titanox "C"	61.7	38.3	8.5	25.6	26.1	40.5	37.9
Zinc Oxide	51.5	48.5	7.1	25.0	25.2	39.7	30.2
High Strength Lithopone	66.8	33.2	10.9	23.9	23.8	37.2	33.9
Titanox "B"	67.4	32.6	11.4	22.8	23.1	33.5	31.8
Antimony Oxide	65.5	34.5	11.4	22.2	22.1	29.6	30.9
Lithopone	64.5	35.5	10.2	21.8	24.0	28.7	30.0
Zinc Oxide 35 per cent Leaded	70.3	29.7	13.8	17.6	17.8	25.4	23.6
Basic Lead Carbonate	77.2	22.8	18.1	14.7	14.0	17.3	22.9
Basic Lead Sulfate	73.5	26.5	15.9	12.0	12.7	15.5	14.3

TABLE III.—HIDING POWER OF EIGHT BRANDS OF HIGH-GRADE COMMERCIAL HOUSE PAINTS.

	Cryptometer, sq. ft. per gal. of Paint	Linoleum Brush-out Method, sq. ft. per gal. of Paint	Ratio, Linoleum Results to Cryptometer Results
Paint A	234	289	1.24
Paint B	196	263	1.34
Paint C	195	246	1.26
Paint D	192	229	1.19
Paint E	165	202	1.22
Paint F	163	198	1.21
Paint G	159	193	1.21
Paint H	133	185	1.39
Average	....	....	1.26

Table I shows the precision which can be obtained by various operators using this test. Operators 1 and 2 were technical men, while the results reported under operator 3 included those obtained by a janitor, a stenographer, an office girl, and a laboratory assistant.

A series of eleven paints were prepared during the course of the investigation, and the results obtained by this method, as compared to those using the Pfund cryptometer, are given in Table II.

Eight high-grade commercial house paints were also tested, and the results on these are presented in Table III.

CONCLUSIONS

It has been found in this investigation that the results obtained by the linoleum brush-out method are higher than those using the cryptometer, but they retain the same order of magnitude. This is probably due to the smaller difference in brightness between the black and white backgrounds. Good results can be obtained by different operators if proper care is observed.

[For Discussion on Hiding Power of Paints, see page 903.—ED.]

HIDING POWER AND TINTING STRENGTH OF WHITE PIGMENTS[1]

BY R. L. HALLETT[2]

SYNOPSIS

This paper describes a method for making hiding power and tinting strength determinations for white pigments. It establishes relationship between hiding power and tinting strength by means of which tinting strength determinations can be accurately and readily calculated into hiding power units. The relationship established is based on experimental work covering determinations of the tinting strength and hiding power of twenty different white pigments.

For many years the hiding power of the white pigments has been of great interest and importance to the paint industry. The American Society for Testing Materials defines hiding power as:[3]

> *Hiding Power.*—The power of a paint or paint material as used to obscure a surface painted with it.
>
> In this definition the word "obscure" means to render invisible or to cover up the surface so that it cannot be seen.

In practical painting work the hiding power of a paint is its ability to obscure a surface over which the paint has been applied in the form of a practical paint film. Likewise the hiding power of a pigment is its ability to obscure a surface when a paint in which the pigment is used has been applied to the surface in the form of a practical paint film.

In discussing the hiding power of the white paint pigments, it is reasonable to consider the hiding power as the ability of the white pigments to hide a black surface when paints in which the pigments are used are spread over the black surface.

Many methods have been proposed for measuring the hiding power of white paints, some of them making use of more or less complicated optical instruments, and the hiding power figures reported for the various white pigments have varied considerably. To eliminate the confusion which exists, our laboratory for some time has been working on accurate determinations of the hiding power of the white pigments when used in paint, hoping to establish reliable hiding power figures in absolute units to which results obtained by all methods can be referred.

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[1] Contributed by the Research Laboratories of the National Lead Co.

[2] Chemist, National Lead Co., Brooklyn, N. Y.

[3] Standard Definitions of Terms Relating to Paint Specifications (A.S.T.M. Designation: D 16 – 24), 1927 Book of A.S.T.M. Standards, Part II, p. 346.

Realizing that the actual brushing of the paint on the surface to be hidden is fundamentally sound and is the one hiding power method which is not open to either scientific or practical criticism, we have based our hiding power determinations on the brush-out method, but have elaborated the method and carried it out in such a manner as to give extremely accurate and reliable results.

During the past year, we have secured samples of twenty white pigments obtained from actual commercial deliveries representing the best commercial grade of each pigment. We prepared twenty practical paint mixtures, using one white pigment in each paint and using for the vehicle of each paint a pure, pale, quick-drying, boiled linseed oil containing no volatile matter.

Because of the very great differences in hiding power of the twenty different white pigments, due principally to the great variations in refractive index, it was not possible to make all of the paints with the same volume proportions of pigment and vehicle and the different paints were made with pigment and vehicle proportions which produced paints with practically the same volume hiding power. The paints so made were used in the hiding power tests.

HIDING POWER METHOD

Apparatus.—The apparatus consisted of a small container for the paint, a 2-in. flat varnish brush, a suitable sensitive balance and 20 smoothly finished poplar wood panels. The wood panels were each 30 by 10 in. and were about $\frac{3}{4}$ in. thick. The panels were first prepared by applying a priming coat and a suitable number of smooth flat undercoats of a white paint which had a light reflection value of 84 per cent. The panels were then painted along the center with a flat black stripe 2 in. wide, extending the long way of the board. The black stripe had a light reflection of 4.5 per cent.

Method of Test.—Each white paint was spread over one black line panel using a spreading rate which would result in more than eight coats being required to give complete visual hiding. After the first coat was dry, a second coat of each paint was applied on its respective panel covering the entire panel with the exception of a 2-in. strip at one end. Succeeding coats of each paint were put on in the same way, each coat leaving an unpainted 2-in. strip of the preceding coat, until the last coat on each panel gave complete visual hiding of the black line, as determined by careful inspection by a group of trained observers. Such a large number of coats was used on each panel that a single coat represented a comparatively small percentage of the whole. In some cases it was obvious that only part of the final coat was required to complete the hiding and an estimation was made of the proportion of the last coat which should be included so the end point was quite accurately determined even to a fraction of the last coat.

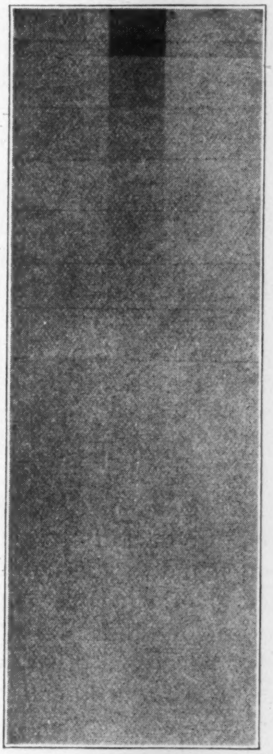

FIG. 1.—Showing a Hiding Power Panel with the Different Coats Applied.

The spreading rate and actual weight of paint used for each coat on each panel were accurately determined by weighing the paint, container and brush before and after application of the paint. Each coat was carefully brushed and cross brushed until it was perfectly even and showed no perceptible visual differences in the hiding of the black line. After the final coat was applied, the total weight of paint and the total weight of pigment on a unit surface were carefully calculated for each panel. The figures expressed in absolute units showing the weight of each pigment on a unit surface required to give complete visual hiding represent the hiding power of the different pigments.

Figure 1 is a photograph showing one of the hiding power panels with the different coats applied and illustrates the hiding power method.

The careful manner in which these tests were made and the great care used in controlling the application of the paint and checking all of the calculations has resulted in hiding power figures for these white pigments which are extremely reliable and may be considered as the true hiding power of these white pigments as they are commercially being made today.

TINTING STRENGTH

For a number of years our laboratory has made a careful and comprehensive study of tinting strength methods and the tinting strength of pigments. The tinting strength of a pigment cannot readily be quantitatively reported in absolute units and is essentially a relative property which must be referred to a standard pigment selected as the basis for comparison.

As the work on tinting strength methods progressed, it was found that two different factors are of great importance and apparently have not been realized in many of the tinting strength methods which have been proposed and used. In making tinting strength determinations it is most practical to make the comparisons with the pigment-tinting material mixtures in the form of fairly stiff oil pastes. The first important factor which was found to affect tinting strength determinations is the consistency of the pastes used. It was conclusively proved that two white pigments which bear a certain definite quantitative tinting strength relation to each other, when pastes of a certain consistency are used, can show quite different tinting strength relation when pastes of a different consistency are used. It is necessary to select a standard paste consistency and use pastes of the standard consistency in making all tinting strength comparisons between the pigments.

In testing the tinting strength of the various white pigments as compared to a standard white pigment, it also was found that quantitative tinting strength relations determined by matching pastes of a certain degree of brightness or light reflection are often quite different from the tinting strength relations determined by matching pastes having a considerably different degree of brightness or light reflection.

Therefore, to determine accurately the relative quantitative tinting strength of different white pigments as compared to a standard white pigment, it is necessary to adopt a carefully standardized tinting strength method in which all of the pastes used for comparison have substantially the same consistency and in which all of the pastes used for comparison have substantially the same degree of brightness or light reflection after the tinting material has been added. These are the two important factors to be considered and unless both of these precautions are observed tinting strength determinations will be unsatisfactory and unreliable. With these limitations thoroughly proved and understood, a standard tinting strength method was developed which has given great satisfaction.

TINTING STRENGTH METHOD

Apparatus.—The apparatus consists of a glass plate, a spatula standardized as to size and flexibility, and a weighing bottle or burette for dispensing the oil.

Materials.—The materials required are the standard white pigment which is to be taken as the basis of comparison, a standard black pigment which is to be used for tinting the white pigment and standard refined linseed oil. In all of the tinting strength work reported in this paper the standard white pigment was basic carbonate white lead of good commercial grade, although for convenience, many of the determinations were actually made by comparing with a standard sample of Titanox "B" which was previously carefully standardized against the basic carbonate white lead standard sample. The black tinting material used was the finest lampblack, diluted with the finest precipitated calcium carbonate so as to minimize errors in weighing very small amounts of the black pigment.

Method.—One gram of the standard white pigment and the proper amount of the standard black tinting material are weighed and placed on the glass plate. The amount of black tinting material used is that amount which when mixed with the 1 g. of standard white pigment and worked into the form of standard paste with the linseed oil will produce a paste which has a light reflection of exactly 20 per cent. The linseed oil is then added to the dry white and black pigments in amounts necessary to produce paste of standard consistency. After the oil is added, the standard white pigment, standard black tinting material and oil are worked into a smooth paste and are then rubbed continuously for three minutes with the spatula.

All of the white pigments to be tested are treated in exactly the same way, using 1 g. of each white pigment and the amount of standard black tinting material necessary to produce a gray paste which will exactly match the standard gray paste. Sufficient oil is used with each sample to produce a paste with approximately the same consistency as the standard paste. A sufficient number of gray pastes are rubbed up with each sample using different amounts of black tinting material until a gray paste is obtained which exactly matches the stadard gray paste. The relative tinting strength of the sample being tested is the weight of black tinting material required for the sample divided by the standard weight of black tinting material used with the standard sample in the standard gray paste.

Tinting strength determinations were made with all of the twenty white pigments referred to, comparisons being made with basic carbonate white lead, as the standard which was given an empirical tinting strength of 100.

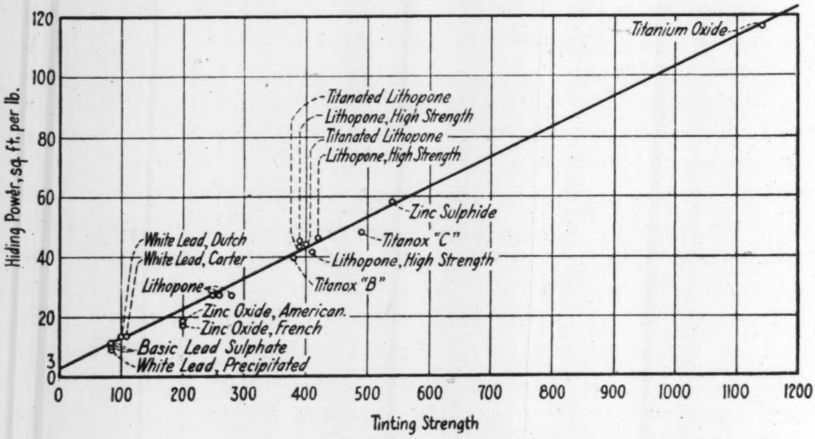

FIG. 2.—Showing the Relation of Hiding Power and Tinting Strength of the Twenty White Pigments.

Figure 2 shows a plot of the twenty white pigments with the tinting strength plotted as the horizontal coordinate and with the hiding power in square feet per pound plotted as the vertical coordinate. These results clearly demonstrate that when a proper tinting strength method is used and the necessary precautions discussed in this paper are followed, there is a definite straight line relation between tinting strength and hiding power. The plotted points obviously fall on a straight line, and the relationship is so clearly proven that when a point does not fall exactly on the straight line, it must be considered that the point is incorrectly placed because of experimental error. The determination of hiding power is difficult and tedious, but the determination of tinting strength is easy and reliable when the proper precautions are used, which means that hiding power may accurately and easily be found by determining tinting strength and calculating tinting strength to hiding power.

In Fig. 2 the straight line was not drawn in, simply connecting the points, but was accurately located by calculation. Lines were established connecting each point with every other point and all such lines were then extended to intercept the hiding power or tinting strength axis. An arithmetic average of these different intercepts showed that the average line passed through the vertical coordinate at a point about 3 units above the zero hiding power - zero tinting strength origin.

A second point on the average line would be the point representing the average tinting strength and average hiding power of the twenty white pigments. The aveiage tinting strength of the twenty white pigments was 350 and the average hiding power was 38 sq. ft. per lb. The average line was therefore constructed by drawing it through the 3 unit point on the vertical coordinate and through the point corresponding to 350 tinting strength and 38 sq. ft. per lb. hiding power. It is evident that after deducting the correction constant of 3 sq. ft. per lb. the hiding power in square feet per pound is directly proportional to the tinting strength and is equal to the tinting strength multiplied by 0.10.

TABLE I.—TINTING STRENGTH AND HIDING POWER OF TWELVE WHITE PIGMENTS.

	TINTING STRENGTH	HIDING POWER, SQ. CM. PER. G.	HIDING POWER, SQ. FT. PER LB.
Carbonate white lead, Dutch process	100	30	15
Carbonate white lead, Carter process	110	30	15
Carbonate white lead, precipitation process	85	24	12
Basic lead sulfate	85	26	13
Zinc oxide	200	40	20
Lithopone	260	54	27
Titanox "B"	380	80	40
Lithopone, high strength	400	88	44
Titanated lithopone	400	88	44
Titanox "C"	450	96	48
Zinc sulfide	540	116	58
Titanium oxide	1150	230	115

The average line intercepts the vertical hiding power axis at a point above the horizontal tinting strength axis which indicates that, for pigments similar in color and brightness to those used for making the plot in Fig. 2, when the limit is reached and such pigments have no tinting strength they will still have some hiding power. This is probably due to the fact that paints made with these pigments have considerably less than 100 per cent brightness and absorb a considerable part of the light which strikes them. The appreciable proportion of light which is absorbed probably influences the hiding power and gives some hiding power to such paints even when they have no tinting strength.

As this paper has demonstrated that, after deducting a correction constant, hiding power is directly proportional to tinting strength, it is evident that:

The hiding power of any white pigment in square feet per pound is equal to its tinting strength (carbonate white lead basis) multiplied by $0.10 + 3$.

The twenty white pigment samples were tested, but in some cases two or more samples represented the same kind of pigment, the various samples being obtained from different commercial sources of supply representing different manufacture. In each case, the examination of the different samples of the same kind of pigment gave sufficiently similar results to justify the averaging of the results so as to give single hiding power and tinting strength figures for each kind of pigment. In all, twelve kinds of white pigment were studied, and Table I shows the twelve white pigments together with their hiding power in square centimeters per gram, hiding power in square feet per pound and tinting strength. These average figures should prove to be of considerable service in comparing the relative hiding power of different white pigments when used alone or together in paints. They represent actual visible hiding power determinations by a method similar to the generally accepted method of applying and judging paints.

To a certain extent the research work reported in this paper is a continuation and amplification of the work covered in the paper[1] on hiding power presented in 1926. Some of the results given in this present paper differ from those previously reported due to the fact that we now have a better understanding of the test requirements and are using more accurate and sensitive test methods, and also because some of the pigments examined have had some of their physical characteristics changed materially since the previous paper was presented.

Acknowledgment.—I wish to express my appreciation of the valuable assistance given me by Mr. W. C. Weber, who conducted the experimental work on which this paper is based.

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[1] R. L. Hallett, "Hiding Power of Pigments," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 538 (1926).

DISCUSSION ON HIDING POWER OF PAINTS

Mr. G. S. Haslam.[1]—In commenting upon the very accurate paint-out tests described in the paper by Mr. Hallett, I should like to emphasize as he pointed out that the test cannot be considered a routine test. The 15 or 16 days required for the numerous coats of paint to dry are entirely too long, but if the tinting strength test as developed by the National Lead Co. is an accurate method of measuring this same hiding power, then the tinting strength test is acceptable.

There is one age-old argument which has not been answered satisfactorily and which I feel is very definitely applicable to the analyses that have been made. Let us consider a sample of white pigment, the brightness of which is 90 per cent and to half of this sample we add enough black to give it a brightness of 80 per cent. These two portions are then considered as different pigment samples and the tests just described applied to them. Under no circumstances can there be an increase in tinting strength due to the addition of the black material, and yet it is well-known that there will be an increase in the hiding power with the decrease in brightness caused by this addition.

I do not feel that there is any question that there is an increase in hiding power with an increase in tinting strength over the range of basic carbonate lead to titanium oxide, but I do feel that in differentiating between pigments in a given class there is no relationship between these two factors.

Mr. R. L. Hallett.[2]—The statements made by Mr. Haslam are true, and are generally accepted by every one. The relationship between tinting strength and hiding power which we have developed presupposes white pigments that do not differ too greatly in brightness. Theoretically the relationship is exact for pigments of exactly the same brightness. Practically the relationship is true within practical limits, for nearly all commercial white pigments of good delivery. Of course a white pigment whose brightness differs materially from the others will plot away from the straight line to the extent to which it differs in brightness from the others. We cannot take a gray pigment with very low brightness and compare it with white pigments having very high brightness, but the relationship is generally true with the commercial white pigments of today.

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[1] Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] Chemist, National Lead Co., Brooklyn, N. Y.

MR. G. F. A. STUTZ.[1]—I think that Mr. Hallett is to be congratulated on his very accurate determinations of hiding power and tinting strength and on the fact that he has been able to make them accurate enough to find that an exact straight-line relationship exists where so many other laboratories have failed.

I am sorry that Mr. Hallett was unable to apply his method in the cooperative work of Subcommittee VIII of the Society's Committee D-1 on Preservative Coatings for Structural Materials, where five or six laboratories have all measured the hiding power and tinting strength of six commercial white pigments by their best technique. In this case tinting strength was determined by each laboratory using an identical method, with the same tinting black pigment, the same oil, and the same procedure in every detail. In fact, the method used was the Society's tentative method which was withdrawn in 1929.[2] The agreement by this method between the six laboratories was very much less satisfactory than was the agreement between the same group when it determined the hiding power of the same materials using the Pfund cryptometer. Reference to the report of Committee D-1[3] will show figures which indicate that the Pfund cryptometer enables one to determine hiding power more accurately than it is possible to determine tinting strength. I hope that Mr. Hallett will be able to use his hiding power and tinting strength methods on these pigments.

He raised a question as to the determination of the end point in his hiding power test. This seems to us to be one possible source of error in the paint-out test. Dr. Pfund has pointed out that it is more accurate to approach an end point from both sides, but the paint-out test allows us to approach the end point only from the side of incomplete hiding. I wonder if Mr. Hallett resorted to the cryptometer to tell when he got to the 98-per-cent point? If so, do the figures agree with tinting strength as do those of complete hiding? Were complete hiding and the 98-per-cent point found to be identical?

MR. HALLETT.—We regret that we were unable to take a greater part in the testing of the pigments examined by Subcommittee VIII. The testing of the 20 pigments discussed in this paper consumed such a large amount of time and monopolized the services of our research workers in this particular department to such an extent that we were unable to proceed with the work of Subcommittee VIII much as we desired to do so. We hope to be able to test some of the pigments studied by the subcommittee and we are inclined to think that the erratic tinting strength results obtained in the past are perhaps due to the fact that the precautions discussed in this paper have not been completely understood.

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[1] Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] Tentative Method of Test for Mass Color and Tinting Strength of Pigments (D 282 - 28 T), *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part I, p. 885 (1928).

[3] *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 748 (1930).

Mr. Stutz has asked about the end point in our paint-out tests. In painting the panels, we applied from 8 to 16 coats on each panel and we made photometric readings after each coat was applied. We found that the photometer was not able to determine differences perceptible to the eye and the photometer indicated that the end point had been reached when the eye could still perceive some lack of hiding and could determine that an additional coat of paint was required. We had no difficulty in accurately determining the end point by masking the lower part of the panel and viewing only the top part above the mask. As we started to raise the mask we could continue to see the black line up to a certain point above which we could not see the black line and the end point was reached. This method of determining the end point is very accurate and in some cases we were even able to estimate as closely as half of the last coat, it being obvious that on some panels only part of the last coat was required to give complete visual hiding. The end point error was probably not greater than 5 per cent on practically all of these panels and on some of them was considerably less than 5 per cent. A number of the paint-out tests were repeated several times and the repeat tests checked very closely in all cases. The paint-out test as we conducted it is fairly long and tedious but can be greatly simplified by applying most of the coats in the form of one to three very heavy coats to give almost complete hiding and then finishing with two or three of the very thin coats to give the accurate end point.

MR. P. H. WALKER.[1]—In regard to the paper by Messrs. Stutz and Haslam, I wish to call attention to what appears to be an omission in the description of the modified whirling apparatus. If that apparatus consists of an arm on which a panel is spun off center, you will not get a uniform film. In fact, in Mr. Haslam's paper in *Industrial and Engineering Chemistry*, the analytical edition of January, he says that a non-volatile vehicle is used and that it is necessary to use a vehicle that gives a pigment and oil mixture with no yield value; otherwise a variable film will be obtained, bodied linseed oil has been used satisfactorily. Now, if you have that vehicle, why use a spinning device? You could get a uniform film with a brush if you have no yield value. If the apparatus however was modified by properly designing so as to rotate around the center axis and also rotate the plate around its axis it might be possible to get a uniform film with a paint.

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[1] Chemist, U. S. Bureau of Standards, Washington, D. C.

MR. HASLAM.—Replying to Mr. Walker, the reason the spinning film method has an advantage is that, when you use a perfect vehicle for the determination of the hiding power of pigments, you can prepare a variable film, by starting with a thick film which is perfectly level and throw off a little paint at a time, whereas you cannot brush off a very little bit or apply a very little bit at a time with a brush and maintain uniformity.

MR. G. W. THOMPSON.[1]—I should like the privilege of presenting to you a theoretical discussion of the hiding power of white paints and pigments based on a conception which I think is perhaps a little new, at least in so far as the mathematical presentation is concerned. It involves the determination of brightness of a number of different surfaces by the use of the photometer. We indicate all of the brightnesses by the designation Br and differentiate between them by sub-designations. We start with a black surface and as this has no coats of white paint applied to it we designate its brightness as being Br_0. Next we determine the brightness of the white paint of a sufficient thickness of coats to give the maximum brightness. As theoretically this would require an infinite number of coats we designate the brightness of the white paint so obtained as Br_∞. The difference between Br_∞ and Br_0 we call the initial brightness range.

Between Br_∞ and Br_0 we may have any number of Br readings which require particular sub-designations. If one unit of white paint is applied to one unit of surface then the brightness resulting would be indicated at Br_1; with two units of paint applied the designation would be Br_2. To generalize, any brightness reading would have the general designation Br_n. Making n equal zero, it is the brightness of the black surface; making n equal infinity, it is the brightness of the white paint.

We have referred to the expression $Br_\infty - Br_0$ as being the initial brightness range. If we make n greater than zero then $Br_\infty - Br_n$ represents any intermediate brightness range, and the expression $\dfrac{Br_\infty - Br_n}{Br_\infty - Br_0}$ represents any intermediate brightness range ratio.

Inasmuch as the theory indicates that each unit coat of paint successively applied reduces the brightness range ratio according to a certain constant to be determined, then this constant would be C^1 where one unit coat of paint has been applied and C^2 where two unit coats have been applied, and so on *ad infinitum*. We may construct the following general equation:

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[1] Chief Chemist, National Lead Co., Brooklyn, N. Y.

$$\frac{Br_\infty - Br_n}{Br_\infty - Br_0} = C^n$$

Obviously, as Mr. Pfund has stated, there should be an agreed upon point where complete hiding has been obtained. For practical purposes we may assume that when C^n equals 0.02 complete hiding has been obtained.

Now suppose we are applying paint over a black surface without any regard in the application of getting exactly a unit amount of paint on the surface. The amount of white paint applied may be more or less than the unit amount. Whatever it is, it is n units of paint and n may be any number or fraction thereof. When after one coat of indefinite amount has been applied and the amount determined in units of paint applied, it is easy enough to calculate what the brightness range ratio would be for any number of units of white paint applied or fractions thereof. If we have calculated the brightness range ratio where one unit of paint has been applied, then we can calculate the number of coats of paint that need to be applied to get a brightness range ratio of 0.02. This is the main thought that I want to give to you. We have made brightness determinations on the painting tests conducted by Mr. Hallett and while I have not been personally able to follow this work, I am told that the brightness readings and the brightness range ratios obtained therefrom conform in general step by step to the principle here presented. We have demonstrated that with successive thicknesses of lens paper and determining the brightness over black, the principle enunciated has been found correct.

I have only one more thought to present in this matter. Suppose we plot on plain logarithmic paper, the plain scale being n, that is, the number of thicknesses of coats applied, and the log scale giving the brightness range ratios, we obtain a straight line running from 1 on the brightness range axis to some point at 0.01 on the n axis. We can make the n axis 0.02. This may require slight correction for pigments of differing brightness but substantially it indicates the principle involved.

Now with tinting power we get a line which is somewhat parallel to the hiding power line with a curve at its origin, which indicates the close relationship between tinting power and hiding power properly tested out. The tinting power tests, however, are not conducted as ordinary tinting power tests are conducted, but we start with the unit amount of black and add successive amounts of white pigment with oil.

What I have offered is simply a scheme whereby if one takes a black board of a definite area and paints over it a single coat of white paint, by having determined the brightness of the black board, the brightness of the white paint of nominally infinite thickness, and the brightness of the white single coat of paint supplied, you should be able to calculate the hiding power of the paint in terms of the amount of white paint needed to get nominally complete hiding.

MR. F. C. SCHMUTZ.[1]—I would like to ask Mr. Pfund a question pertaining to his instrument. Has he ever attempted to use duplicate photo-electric circuits, thus making simultaneous readings over the black and white areas? Connecting both circuits with a potentiometer would permit evaluating the difference of the two areas with only one reading.

MR. A. H. PFUND.[2]—It is impossible to obtain two photo-electric circuits that maintain equal sensitivity.

MR. F. G. BREYER.[3]—My comments in respect to hiding power come under three heads. First, I am extremely gratified with the work that Mr. Hallett has done in bringing the tinting strength and the cryptometer readings together. However, there is no question but that, in the last analysis, the most important test is the test of actually applying the paint and determining with the ordinary eye whether or not it does hide, and Mr. Gardner has taken what I would call the strictly practical standpoint with respect to the hiding power of those pigments. We have all known it; Mr. Gardner has simply made a little more rigorous the method of brush-out test than what has been used in a great many of the laboratories. I recall particularly the brush-out test Lowe Brothers have been using for a great many years on paper. The Lowe Brothers' test measured the value of the pigment within as close a degree as necessary for the practical paint manufacturers; although it was very disconcerting to have the hiding power test on which most of the pigments were developed fail to check with the practical paint-out test. All the high tinting strength pigments were developed on the tinting strength test, and not very much on the cryptometer and other strength or hiding power readings. What the paint man wants, as expressed in terms of the price he is willing to pay and the preference he gives, is neither brightness alone nor hiding power alone, but the combination you seem to get in the tinting strength test, and that probably accounts for the fact that the development of the white pigments and their increasing use has been the result of increasing the tinting strength and brightness at the same time. Perhaps our next move is to have a little less whiteness with a little more hiding power at a little less cost; because it is the taking out of that last bit of color that raises the cost.

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[1] Paint Section, Research Division, New Jersey Zinc Co., Palmerton, Pa.

[2] Professor of Physics, Johns Hopkins University, Baltimore, Md.

[3] Singmaster & Breyer, Metallurgists and Chemical Engineers, New York City.

The next point is perhaps not quite so pertinent to the papers but it has a bearing and is important to the paint manufacturers. The hiding power tinting strength work is getting up on a flat part of the curve of diminishing returns; that is, we are beginning to split hairs. It has been about 17 years since anyone has come forward with a pigment or a pigment material that has anything new. It was about 17 years ago that titanium oxide was discovered as a paint pigment by Mr. Schroeder. Mr. Schroeder has explained his discovery in that he was analyzing titanium compounds for Dr. Rossi, the original worker at Niagara Falls on titanium, and got titanium hydrate and heated that and got titanium oxide, and this stuff looked good to him and he rubbed it out in oil and decided that it was a good paint pigment. He had not the slightest idea about a cryptometer or any other accurate measurement, but he knew perfectly well how to discover a new pigment. I feel that, with all of our great increase in scientific accuracy in the measurement of pigments, the past 17 years have been somewhat barren in the way of discovering anything entirely new and I believe that some of our laboratory efforts could be very well diverted toward seeing if we can find something else to help us along. We have not exhausted all the possibilities of titanium oxide, but are beginning to get near the top.

Attention should not be confined to the pigment alone in endeavors to improve white paints. If it is realized what could be done to improve the hiding power of carbonate of lead by reducing the refractive indexes of vehicles a little bit, one can realize what possibilities are ahead. Perhaps there is some basic reason why vehicles cannot be made of lower refractive index, but there is a whole range of possibilities that have not been touched.

MR. HALLETT (*closure by letter*).—I greatly appreciate the friendly discussion of our paper. Comments of this kind are always useful as a guide for future work and frequently clear up doubtful questions. This paper and the discussion clearly show the definite relationship between the tinting strength and hiding power of white pigments. The paper indicates the precautions necessary in conducting tinting strength determinations but it is not simply a matter of chance that the empirical procedure adopted develops the direct relation between tinting strength and hiding power because if the tinting strength method is conducted according to any other empirical procedure the direct relationship will be just as definitely shown if all tinting strength determinations are made under identically the same conditions, although the factor for converting tinting strength to hiding power may be different and the straight line may make a different angle with the horizontal axis but will nevertheless be a straight line and show the direct relationship.

GLOSS AND ITS QUANTITATIVE MEASUREMENT

By E. D. Ries[1] and C. B. Gilbert[2]

Within the last few years, considerable attention has been given to the question of measuring gloss quantitatively. The problem was first brought to our attention in 1928 by an industrial concern when difficulty was encountered in measuring gloss on panels coated with colored lacquer. Differences in gloss readily apparent to the eye could not be detected by means of instruments then available.

Recently, Pfund[3] has given a very able discussion of this question. He points out that what paint and lacquer manufacturers are interested in is the true smoothness of the surface, his so-called "objective gloss," or putting it another way, the closeness of approach of a surface to that of an optically smooth surface. The problem thus becomes one of comparing the intensity of light specularly reflected from a surface to that reflected specularly from an optical surface. The difficulty lies in separating specular from diffuse reflection, which in the case of colored panels becomes one of overcoming the tinting of the reflected beam. The Pfund instrument does this by limiting the size of the reflected beam. The method here described makes use of the flicker photometer to overcome the color and measures the diffuse as well as the specular light. This latter method has several important advantages, which will be brought out and discussed later.

Some standard of gloss must be used. We measure gloss qualitatively by eye by estimating how good a mirror the surface appears to be. Instinctively, we think of an optically smooth surface as having 100 per cent gloss. Since this type of surface will reflect the maximum amount of specular light to the eye, this serves as an excellent standard to which all other intensities of reflected light may be referred.

The apparatus used in this work consists essentially of a framework for holding the specimen panels in a vertical position and so arranged that they can be turned about an axis passing through the vertical center line of the panel surface; a flicker photometer, which takes care of the color effects; two light sources, one of which is a calibrated standard; and lenses and screens. A diagrammatic sketch of the optical system is shown in Fig. 1. The panel holder has a pointer P_1 attached to it which indicates on a graduated circle (the center of which lies in the axis of rotation of the holder) the angle which the plane of the specimen makes with AF.

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[2] Hercules Powder Co., Parlin, N. J.

[3] A. H. Pfund, *Journal*, Optical Soc., Vol. 20, No. 1, p. 23 (1930).

The source of light is placed in a small metal housing at S_1. An arm fastened to the top and extended beyond the front of the housing serves to hold the light source in place at a constant distance from the specimen. The axis of the specimen holder passes through the center of the arm and allows the lamp to be moved to any angle. Thus both the specimen and the light source revolve about a common axis independently of each other.

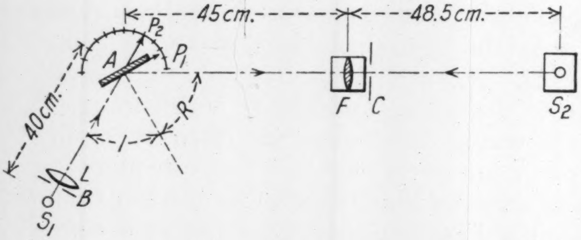

FIG. 1.—Diagrammatic Sketch of the Optical System.

A pointer P_2 attached to the far end of the arm serves to indicate on the graduated circle the position of the lamp S_1 with respect to the line AF. A collimating lens L is attached to the housing between the lamp and the specimen in order to render the light beam parallel. A tin screen B with a $\frac{1}{2}$ in. circular opening is placed between the lens and the lamp to reduce the size of the beam. A 400-watt, 115-volt lamp is used as light source. In order that the pointer P_2 should indicate the path of the beam of light from S_1, it is necessary to have the pointer, the axis of rotation of the lamp, the center of the lens, the center of the screen opening, and the center of the lamp all in the same vertical plane.

The flicker photometer, F, is mounted so that the beam of light reflected from the surface of the specimen strikes the center of the beveled edge of the photometer disk.

Another screen C is necessary on the right-hand side of the photometer in order to prevent any light from passing around the disk and being reflected back to the left side. The opening in the screen C is made so that its upper edge conforms to the edge of the disk, and

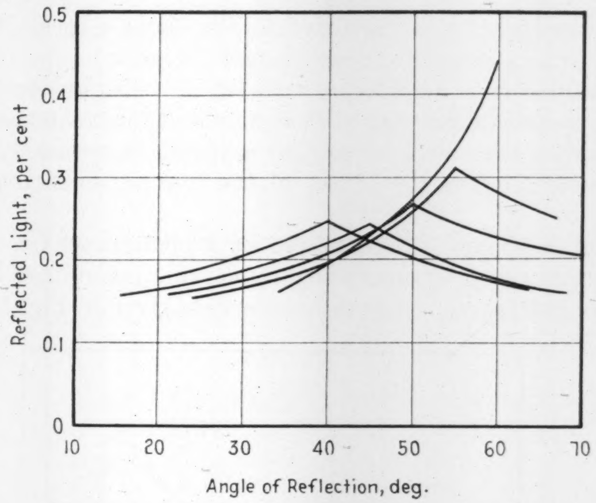

FIG. 2.—Showing Characteristic Curves of "Semi-Flat" White Panels.

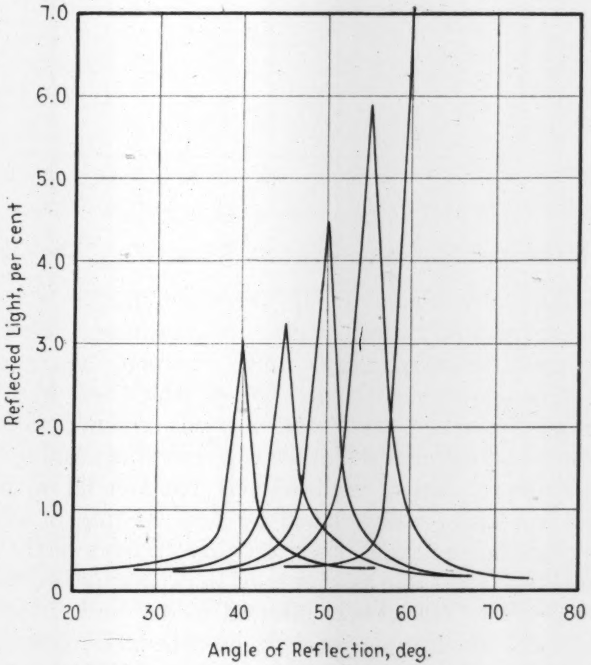

FIG. 3.—Showing Characteristic Curves of "Polished" White Panels.

has a flat horizontal piece fastened to its upper edge so that any light which comes from the specimen and passes over the top of the disk is prevented from being reflected back to the right-hand side.

In another metal housing at S_2 is mounted the comparison lamp. A screen with a $\frac{1}{2}$-in. circular opening is placed immediately in front of the housing so that the center of the opening is located in the line FS_2.

The entire apparatus is mounted on a photometer bench. The intensities of S_1 and S_2 are controlled by varying the voltage by means of slide wire resistances. The dimensions are given in Fig. 1.

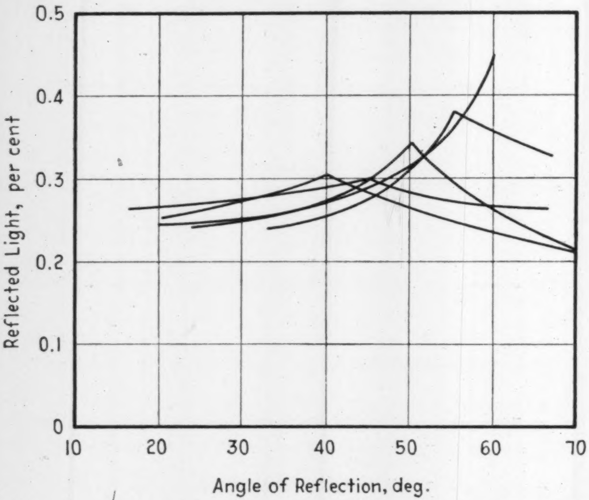

FIG. 4.—Showing Characteristic Curves of "Semi-Flat" Black Panels.

The specimens consisted of 15 sheet-iron panels 4 in. square, coated with lacquers of various degrees of glossiness. Five different colors were used: namely, gray, white, maroon, black, and blue. There were 3 panels of each color; one of which was high in gloss; another less glossy, called "semi-flat" for convenience; and a third which was the same color as the other two, but was absolutely "flat." The first two were coated with regular commercial nitrocellulose lacquers, but the third was finished by first coating it with a thin coating of clear lacquer and then dusting it over with 200-mesh pigment which was the same as that used in preparing the commercial lacquers. The "flat" panel was allowed to dry and the excess pigment shaken off, leaving the surface smooth and completely free from gloss. In the case of the "flat" white panel, a plaster of Paris disk was cast and used in place of the metal panel.

The experimental procedure consisted in setting the panels at various angles to the incident beam and measuring the intensity of the reflected beam. When the angle of incidence was equal to the angle of reflection, the reflected beam consisted mainly of the specularly reflected light together with that amount of diffuse light which is always present at any angle. Due to the finite width of the beam, the intensity of reflection at other angles is not constant but decreases regularly on both sides of the specular angle. At about twenty degrees on either side of the specular angle, the value of the diffuse light becomes practically constant and can be used as its measure. These readings checked those taken on the absolutely "flat" panels.

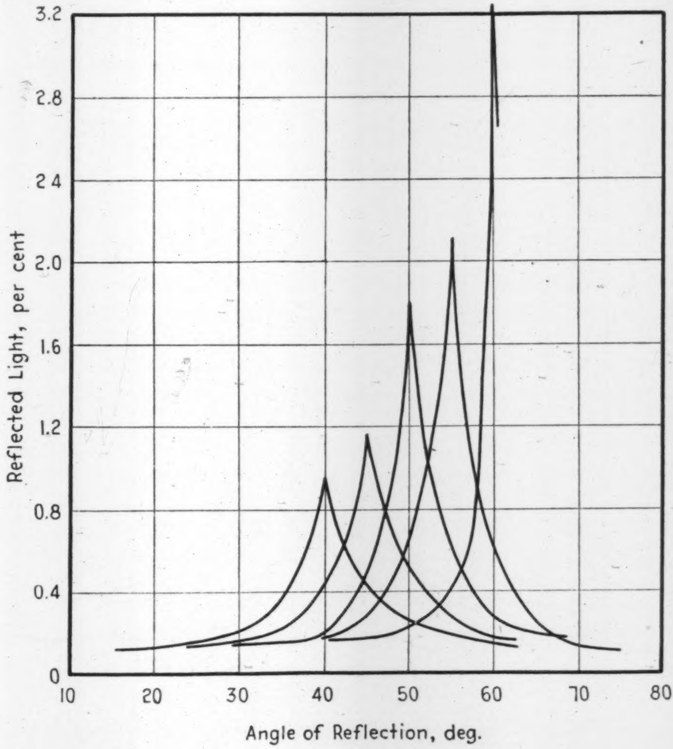

FIG. 5.—Showing Characteristic Curves of "Polished" Black Panels.

Readings were obtained directly in terms of relative intensity. In order to convert these into terms of per cent reflected light it was only necessary to swing S_1 (Fig. 1) into line with S_2, the standard lamp, and then to determine the relative intensity of S_1. Using this as a basis all previous readings divided by this quantity gave percentage of light reflected.

Figures 2 to 8 are characteristic curves of a number of panels. The gray and the maroon panels gave curves similar to these. The maxima are plainly evident, except in the case of the "flat" panels (Fig. 8), and correspond to the case where the angle of incidence equals the angle of reflection. The absence of maxima in the case of the "flat" panels gives the best indication that they are absolutely free of gloss. It should be noticed that the intensity of the diffuse light as measured by the asymptote which the lower ends of the curves approach is very definitely dependent on color, that for white being higher than for any of the others. Furthermore, the estimated position of the asymptotes agrees very well with the determinations on the "flat" panels of the same colors, showing that a fairly accurate figure for the intensity of the diffuse light can be obtained from measurements on glossy panels.

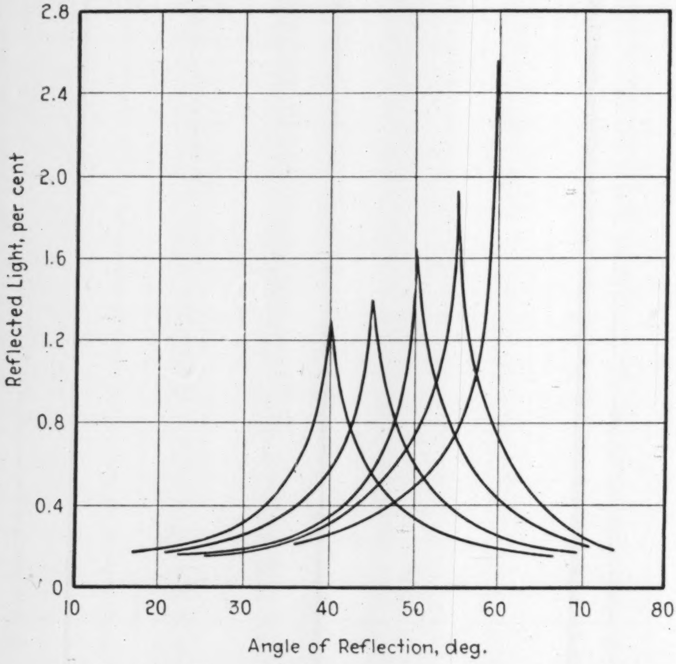

FIG. 6.—Showing Characteristic Curves of "Semi-Flat" Blue Panels.

The values of the maxima in the various curves are obviously determined by the sums of the specular and diffuse light reflected

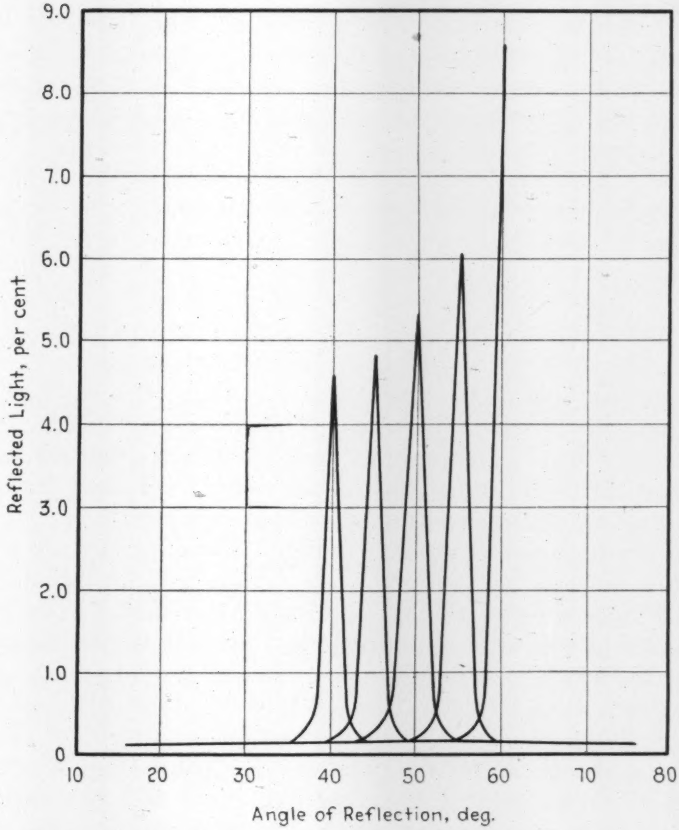

FIG. 7.—Showing Characteristic Curves of "Polished" Blue Panels.

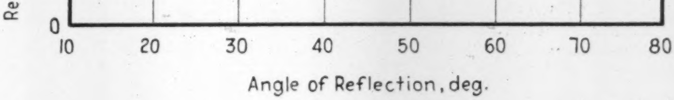

FIG. 8.—Showing Characteristic Curves of "Flat" Panels.

from the panel. The lower asymptotes, or, what amounts to the same thing, the curves of Fig. 8 measure the intensity of the diffuse light. Therefore, by subtracting the latter quantity from the former, values for the intensities of the specularly reflected light are obtained for any angle of incidence. These values are plotted in Fig. 9.

In Fig. 9 also are plotted the theoretical intensities of specular reflection from optical surfaces of different indexes of refraction, calculated by means of Fresnel's laws.[1] The index of refraction for the panels was found by total reflection methods and was equal to 1.62.[2]

DISCUSSION

Referring first to the theoretical standards, the advantages of using them are obvious. They are completely reproducible and show no changes due to deterioration, dust, scratching from wiping, etc. They cost nothing. Furthermore, the correct standard for a substance of any given index of refraction is always available.

On the basis which we have outlined above, percentage of gloss may then be expressed at any angle as the ratio of specular light reflected from a panel to that from the theoretical surface of the same index of refraction, multiplied by 100. It is particularly important to have the correct standard in the case of panels of high gloss, since a small change in the index of the standard means a correspondingly larger change in the percentage of gloss. For example, comparing the curve for the polished blue panel (Fig. 9) with the theoretical curve, index 1.62, at 50 deg. gives 68.5 per cent gloss against 78.8 per cent gloss when compared with the theoretical curve, index 1.55. The difference in index of refraction is only 4.3 per cent. Corresponding values for "semi-flat" black panels are 1.84 and 2.12 per cent, respectively.

Attention is called to the fact that the intensities of specular reflection increase with increasing angle of incidence, as required by the theory. It should be noticed, however, that the increase is more

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[1] Drude, "Theory of Optics," pp. 278–283, Longmans, Green, and Company, New York (1902).

[2] The final form of the Fresnel equations for calculating the intensity of specularly reflected light is:

$$I_2 = \frac{I_1}{2}\frac{\sin^2(i-r)}{\sin^2(i+r)}\left[1+\frac{\cos^2(i+r)}{\cos^2(i-r)}\right]$$

where I_1 = intensity of incident beam,
I_2 = intensity of reflected beam,
i = angle of incidence, and
r = angle of refraction.

r can be found from the relation:

$$\text{Index of refraction} = n = \frac{\sin i}{\sin r}.$$

rapid than can be accounted for by theory. According to Chwolson,[1] when dealing with surfaces not optically smooth, light can be reflected specularly only when $h \cos \phi$ is small compared to the wave length of the incident light, h being the depth of the unevennesses, and ϕ the angle of incidence. With increasing angles of incidence, $h \cos \phi$ becomes smaller and specular reflection consequently increases due to this factor alone. The net result in the curve is the sum of the two. One might expect that two curves, having about the same values at a 40-deg. angle of incidence, for example, would follow each other in going toward greater angles. This is not necessarily the

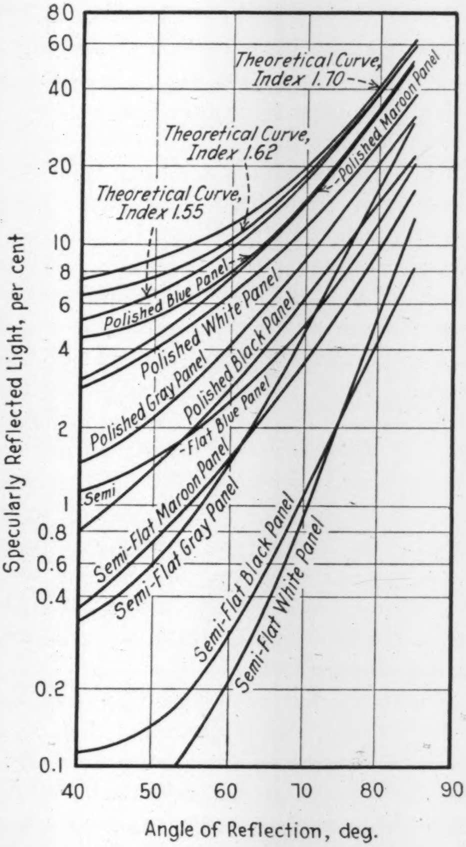

FIG. 9.—Showing Relation of Specularly Reflected Light to Angle of Reflection.

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[1] Chwolson, *Lehrbuch der Physik, Zweite Auflage*, Vol. II, Part 2, p. 131, Friedr. Vieweg und Sohn, Braunschweig, Germany (1922).

case as can be seen from the curves in Fig. 9 for the "semi-flat" maroon and gray panels, which cross each other. This result is readily checked by the eye. The probable explanation of this is that the shape of the imperfections is different in the two panels and that their interference with specular reflection, that is, their effective values of $h \cos \phi$, change at different rates. It is therefore clearly evident that values of gloss determined at any one angle are open to serious question. From the shape of the curves obtained, it would seem advisable to determine values at at least three angles—45, 60, and 75 deg. being satisfactory and easy to use.

In dealing with surfaces having an "egg-shell" or duller finish, it is necessary to measure the diffuse light rather than to neglect it or to attempt to eliminate it by limiting the diameter of the beam. In very glossy surfaces this is not the case. Intermediate cases obviously occur and the border lines are determined by the ratio of specular to diffuse reflection. For example, in Fig. 3, the diffuse light varies from about 2 per cent to 9 per cent of the specular, depending on the angle. In Fig. 7, the corresponding values are about 1.5 per cent to 3 per cent. But in Fig. 4, the diffuse is of the same order of magnitude as the specular, namely, 40 per cent to 105 per cent. And for the semi-flat white in Fig. 2, the percentage varies from 140 per cent to 650 per cent! Furthermore, in the set-up used in this work, except in the case of the most glossy panels, the diffuse was sufficiently strong compared to the specular so that the light coming to the photometer was definitely tinted the color of the panel; and in many cases, comparisons of intensity could not have been made without the use of the flicker.

It may occasion some surprise that the so-called diffuse light from the darker panels was only a little less than half of that from the white. Remembering, however, that a semi-gloss surface has irregularities in it of microscopic size and that 200-mesh pigment is rather large from a microscopic standpoint, the explanation is fairly obvious. After all, diffuse reflection is nothing but an integration of a large number of specular reflections from very small surfaces. If these minute surfaces in themselves are glossy, the diffuse reflection may be quite high, regardless of the color of the pigment. Where the "diffuse" becomes higher than the specular, it evidently means that most of the reflecting surfaces are not in the plane of the panel. Notice again, however, that with the very glossy panels, which obviously have the least surface imperfections, the ratio of specular to diffuse is so great that the above considerations become unimportant. The measurement of total reflected light from such panels can be used to express gloss quite accurately; but in weathering tests, for example, as the surface becomes duller, a time is reached when the diffuse reflection can no longer be neglected.

Figure 10 shows the percentage of gloss plotted as a function of the angle of reflection. For all but the very glossiest panels, the values vary with the angle over a very wide range. It is therefore evident that it is not sufficient to specify gloss at any one angle, but that rather the absolute values at various angles should be given. This is particularly true for the duller panels where the change in gloss with increasing angles of incidence is very large.

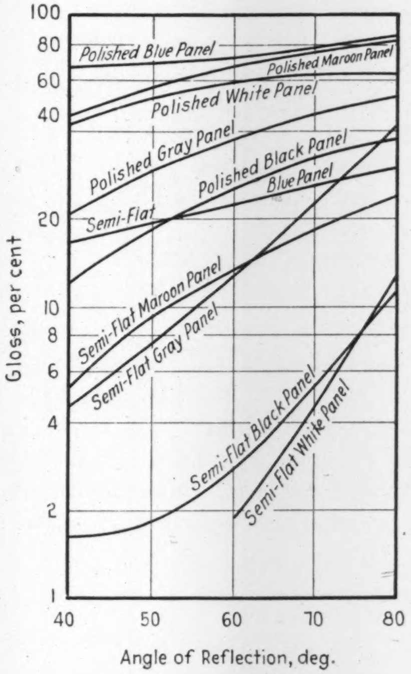

FIG. 10.—Showing Relation of Gloss to Angle of Reflection.

As a general rule, the lower the gloss values at low angles, the steeper the slope. A microscopic study of these panels indicates that the steeper slopes seem to correspond to large numbers of surface imperfections of microscopic size or above. The absolute values of gloss seem to be a measure of the smoothness of those parts of the surface whose imperfections are sub-microscopic. Obviously, for very glossy panels the first type of imperfection is largely absent, resulting in a small slope; but for semi-flat and duller panels a large slope is to be expected.

CONCLUSIONS

1. Gloss is defined as the ratio of the intensity of specular light reflected from a surface to the intensity of specular light reflected from an optical surface of the same index of refraction, expressed as a percentage.

2. A method of measuring gloss has been devised which will work satisfactorily and accurately over the entire range from flat to very glossy surfaces.

3. Theoretical standards have been proposed which can be used for a surface of any index of refraction and which eliminate possible experimental errors from this source.

4. Gloss is shown to change markedly with the angle of incidence, except for the very glossiest panels. The slope of the gloss *versus* angle of incidence curve, in addition to the absolute values, is shown to be of importance.

5. "Diffuse" reflection from darkly pigmented lacquered surfaces has been shown to be of the same order of magnitude as that from light ones.

6. The necessity for measuring diffuse reflection from semigloss and duller surfaces has been shown.

Acknowledgment.—The authors wish to acknowledge their indebtedness to the Hercules Powder Co. for materials and financial aid for this work, and to D. C. Duncan and W. R. Ham of the Physics Department of The Pennsylvania State College for advice and assistance.

DISCUSSION

MR. G. F. A. STUTZ.[1]—I should like to call the authors' attention to a paper by McNicholas in the Bureau of Standards *Journal of Research*, Vol. 1, p. 29, 1928. This paper described an instrument somewhat more complicated than that of the author's and designed to make a number of measurements concerning the reflection of light; among these measurements, it includes such as have been made by Messrs. Ries and Gilbert. The measurements made by McNicholas are somewhat more accurate due to the fact that he has used diffused illumination, whereas Ries and Gilbert have used directed illumination. Under these circumstances, McNicholas obtains a curved line for a matte or flat surface, whereas Ries and Gilbert obtained a straight line.

MR. E. D. RIES.[2]—We wish to thank Mr. Stutz for the reference. Not having seen the paper referred to, I am unable to comment on it.

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[1] Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] Professor of Chemical Engineering, The Pennsylvania State College, State College, Pa.

A METHOD FOR THE DETERMINATION OF THE TRUE ACID VALUE OF OILS, VARNISHES, LIQUID DRIERS AND SOAPS

By E. W. Diener[1] and S. Werthan[1]

Synopsis

A method for the determination of acid value is given which eliminates inaccuracies due to the dissociation of metallic soaps. The metals present as soaps are quantitatively precipitated as insoluble oxalates with the liberation of acid. The procedure is to reflux the sample in an alcohol-benzene mixture with a measured quantity of standard oxalic acid solution and then titrate the total acidity with a standard alcoholic potassium hydroxide solution using phenolphthalein indicator. The difference between this titration and the equivalent of the oxalic acid added is a measure of the true acid value. The method also affords a means for determining the total amount of metallic soaps present.

Data are given establishing the accuracy of the method.

Introduction

The method commonly used in determining acid value consists of dispersing the sample in an alcohol-benzene mixture and titrating with standard alcoholic potassium hydroxide solution. When employing this method for vehicles containing metallic soaps, dissociation results in erroneously high values. The dissociation is not quantitative, and as indicated by fading end points, progresses during the titration.

A method for eliminating this difficulty has been suggested by Neidle[2] in which the dispersed sample is digested with an aqueous mineral acid solution, The metal radical of the soap passes into the water solution as an inorganic salt and the fatty acid radical goes into the solvent layer as free fatty acid. The true acid value is determined by separation and titration of the two layers. In attempting to apply this method, a sharp separation of the layers for titration is often difficult, making the procedure rather tedious. Furthermore, in many cases high values result when titrating the water solution due to the hydrolysis of the soluble inorganic salts. The method proposed successfully overcomes these difficulties.

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[1] Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] Private communication, Mr. Marks Neidle, May, 1926.

THEORY

Metallic soaps are decomposed by the addition of a suitable alcohol-soluble organic acid with the liberation of free acid and the formation of insoluble salts. The total resultant acidity is then determined. The organic acid must be added in a form miscible with the alcohol-benzene solvent mixture usually used so that only one layer will result. Furthermore, the acid must decompose the soaps quantitatively and form insoluble salts of the metals so that they are removed from the system.

Three acids soluble in alcohol, namely citric, phosphoric and oxalic, were investigated. Citric acid apparently does not form insoluble salts of all the metals commonly found in driers, and although some improvement was noted, the hydrolysis of the soluble citrates produces acid reactions. Phosphoric acid forms insoluble phosphates of these metals, but since the tertiary salt forms in some cases and the secondary salt in others, this acid is not satisfactory. Oxalic acid forms normal, insoluble salts of all the metals commonly found in varnishes, extracted paint vehicles and driers, namely, cobalt, lead, manganese, calcium and zinc.

The first step in determining the suitability of oxalic acid was to prove definitely that the precipitation of the oxalates in alcohol-benzene mixtures is quantitative. As representative of the metals usually found, lead, cobalt and manganese soaps were prepared and the metal content determined by analysis. Weighed samples of each soap were dispersed in alcohol-benzene mixtures and refluxed with an excess of oxalic acid. The oxalates were filtered off and the metal content of each precipitate determined. The metal content was calculated from the weight of sample taken and the metal content of the original soap. A comparison of these figures with the results obtained by analyzing the precipitated oxalates is given below:

	METAL CONTENT FROM ANALYSIS OF SOAP, G.		METAL CONTENT BY ANALYSES OF PRECIPITATED OXALATE, G.	
SOAP USED	SET NO. 1	SET NO. 2	SET NO. 1	SET NO. 2
Lead Resinate..........	0.0334	0.1030	0.0339	0.1020
Manganese Resinate....	0.0608	0.0570	0.0607	0.0577
Cobalt Resinate........	0.0513	0.0380	0.0510	0.0372

These results establish that the precipitation is quantitative.

The second factor requiring quantitative verification was the titration of oxalic acid in alcohol-benzene solution with alcoholic potassium hydroxide solution. By standardizing the potassium-hydroxide solution using oxalic acid and also by the usual method using a standard hydrochloric acid solution, the same standardization values were obtained indicating that the titration is quantitative:

STRENGTH OF SOLUTION, MG. OF KOH PER CC.

USING HYDROCHLORIC ACID IN WATER SOLUTION	USING OXALIC ACID IN ALCOHOL-BENZENE SOLUTION
5.34	5.35
5.35	5.33

In the proposed method, the sample dispersed in an alcohol-benzene mixture is digested with a measured amount of standard alcoholic oxalic acid solution, in excess of the amount of soaps present in the sample. The oxalic acid reacts with the metallic soaps to form insoluble oxalates. The excess of oxalic acid, the original free fatty acids and the acids liberated by the oxalic acid are titrated. The difference between this titration and that required for the oxalic acid added is a measure of acids originally present in the vehicle.

METHOD

Solutions:

The following are the solutions used:

1. Tenth normal alcoholic oxalic acid.

Dissolve 6.3 g. of chemically pure oxalic acid $H_2C_2O_4 \cdot 2H_2O$ in sufficient 95-per-cent ethyl alcohol to make a liter.

2. Tenth normal alcoholic potassium hydroxide.

Dissolve approximately 6.6 g. of chemically pure alcohol refined potassium hydroxide (85.86 per cent KOH) in sufficient 95-per-cent ethyl alcohol to make a liter.

3. Neutral solvent mixture.

Seventy-five per cent of 95-per-cent ethyl alcohol and 25 per cent of c. p. benzene.

4. Phenolphthalein indicator.

Dissolve 10 g. of the indicator in 1 liter of 95-per-cent ethyl alcohol. Use 1 cc. for titration.

Procedure:

The procedure to be followed is outlined below:

Weigh a 3 to 5-g. sample of the vehicle into a 500-cc. glass-stoppered Erlenmeyer flask. Add 75 cc. of the solvent mixture and warm slightly to aid solution. Add a definite accurately measured quantity (10 to 25 cc.) of the standard oxalic acid solution; for varnishes and ordinary oils, 10 cc. of the oxalic acid solution is sufficient, while for highly concentrated japan driers, more is required.

Reflux the mixture on a hot plate (using a reflux condenser) for about one hour or until the soaps present have been decomposed.

Remove and titrate hot with the standard potassium hydroxide solution using phenolphthalein indicator. As the end point is approached, very vigorous shaking is required. A pink coloration which persists for several minutes is taken as the end point. Titrating hot increases the speed of titration and results in a sharper end point.

A blank containing the same quantity of the standard oxalic acid solution should be run using the same procedure as for the sample.

Calculation:

The acid value is the weight in milligrams of potassium hydroxide required to neutralize 1 g. of oil:

$$\text{Acid Value} = \frac{(a - b)c}{w}$$

where a = cubic centimeters of potassium hydroxide for sample,
b = cubic centimeters of potassium hydroxide for blank,
c = milligrams of potassium hydroxide per cubic centimeter, (value of standard potassium hydroxide solution), and
w = weight of sample.

Estimation of Amount of Metallic Soaps:

If the vehicle is sufficiently soluble in the alcohol-benzene mixture, the oxalates can be filtered off and washed. The acid value can be determined by titrating the filtrate. The metal content can be estimated by dissolving the precipitate in dilute sulfuric acid and titrating hot with standard potassium permanganate solution, providing not more than one metal is present.

EXPERIMENTAL DATA

The results of some typical determinations are given below:

MATERIAL	ACID VALUE, USUAL METHOD	ACID VALUE, NEW METHOD
Lead-Manganese Liquid Drier	11.8	4.6
Liquid Drier	21.3	1.1
Lithographic Varnish	10.5	10.4
Extracted vehicle from paint	3.9	2.8
	3.4	2.6
	3.5	2.0
	2.2	1.6
	2.4	2.0
	2.2	1.5
	1.8	0.2
	3.0	3.0
	3.1	2.5
	3.4	2.0
	2.5	0.6
Acid Refined Linseed Oil	8.8	8.9
Zinc Linoleate (Dry)	....	9.4
Zinc Stearate (Dry)	....	1.0
Lead Linoleate (Dry)	....	0.8
Lead Resinate (Dry)	....	−1.0[a]
Lead Oleate (Dry)	....	−8.0[a]
Cobalt Resinate (Dry)	....	−11.2[a]

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[a] A measure of the basicity of the soap.

A STUDY OF THE PERFORMANCE CHARACTERISTICS OF A 4-INCH 4-PLY RUBBER TRANSMISSION BELT

By J. E. Skane[1]

Synopsis

The object of the investigation was to study the performance characteristics of a 4-in. 4-ply friction belt, under varying loads, speeds and slips.

A 100-hp. Sprague electric dynamometer set was the apparatus used to test the belts. Tests were made under an approximate tension of 23 lb. per inch per ply on the tight side of the belt. Speeds ranged from 1100 ft. per minute on 8-in. pulleys to 4500 ft. per minute on 18 and 24-in. pulleys, and slips varied between 0.25 per cent to a maximum of about 3 per cent.

From the data collected studies were made of horse power *versus* slip in feet per minute and percentage slip; efficiency *versus* horse power transmitted; the relation of slip to fraction of maximum belt tension turned into effective pull; and the relation of the ratio tight side tension to slack side tension, to slip in feet per minute.

The work verifies the work of others that the horse power - slip curve has a definite shape. That is the horse power curve of a rubber belt reaches a maximum at about 1 per cent slip and beyond that point, regardless of the slip, neither increases nor decreases until it begins to slide off the pulleys. The horse power transmitted may be increased and the actual slip in feet per minute decreased by increasing the pulley size, or by increasing the lineal speed on the same pulley size. The efficiency of a 4-in. 4-ply belt will range between 95 and 97 per cent. As the pulley sizes and speeds increase, the ratio of maximum tension converted into effective pull increases and reaches a maximum of 0.835 on 18-in. pulleys at a speed of 4300 to 4500 ft. per minute. The ratio of T_1 to T_2 will be between 3 and 5. The most economical pulley sizes over which to run a 4-in. 4-ply rubber belt are 12 and 18 in.

Introduction

In reading the existing material published on belting, one finds that much has been written on leather belting, by such authorities as Lewis, Kemmerer, Friedrich, Barth, Nagle, Taylor, and others. A few years ago, the Leather Belting Exchange made comparative tests of rubber and leather belting at Mellon Institute and at Cornell University, and more recently Professor Norman of Ohio State University has published tests he has conducted.

The Leather Belting Exchange investigated mainly the transmission properties of leather belts during performance, with an occasional test of rubber belting on one size pulley only.

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[1] Engineer, Manhattan Rubber Manufacturing Division, Raybestos-Manhattan, Inc., Passaic, N. J.

Outside of Professor Norman's studies, therefore, there still remains a lack of available information on rubber belts, for the engineers, the designers, and the men who are using rubber belts in industry. It is with this point in view that this paper has been written.

The belt tested was a 4-in. 4-ply rubber belt. The carcass was 32-oz. duck; that is, a section 42 by 36 in. weighs 32 oz. Between each ply was a skin of high-grade rubber and the surfaces were frictioned surfaces. The edges were folded and down the center on the back side there was a strip of rubber to hold together the butted edges of the folded outside ply.

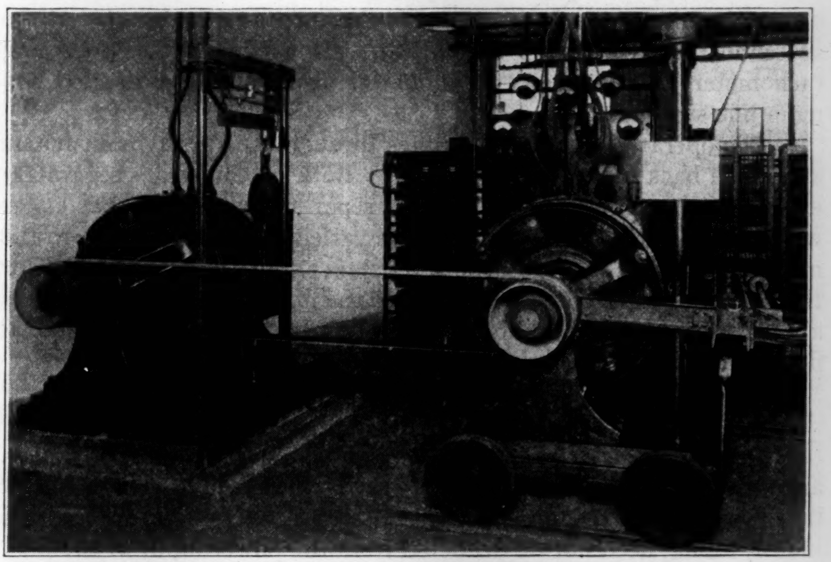

FIG. 1.—Apparatus Used in Performing Tests.

DESCRIPTION OF APPARATUS

The apparatus used in performing the tests is shown in Fig. 1. The equipment consists principally of two electric dynamometers, one of which is used as a motor, or a driver, and the other as a generator, or absorption machine. The motor is a 75-hp. machine with a range of speed of 435 to 1500 r.p.m., while the generator is a 100-hp. machine with a range of speed of 500 to 1500 r.p.m. The motor is fastened rigidly to a concrete base. The generator, mounted on ball-bearing flanged wheels can be moved easily along a level track, thereby allowing an adjustment of center distances to take different lengths of belting. The movable generator is attached by means of a cable to a rigid weighing scale, which measures the total pull on the belt when it is being tested.

Both dynamometers are equipped with torque load scales which measure the unbalanced force on the belts, and both are also equipped with electrically operated speed counters, which check the electric tachometers mounted on the operating panel boards. To the machines is attached a slip meter by means of which may be measured visually the difference in speed of the machines. The slip meter is of the differential counter type, one revolution of the light bulb showing a difference of one revolution between the machines.

The current to operate the dynamometers is taken from the main direct current line, and the control of the apparatus is centered at the switchboard. Upon the switchboard are mounted two recording tachometers, a voltmeter, two ammeters, two field rheostats, and two main line switches.

The operating current circulates through the two dynamometers and is fed back directly into the line. Both machines are separately excited, and both are controlled by a separate rheostat so that loads, which are electrically applied, may be varied at will. Coupled to the machine is a grid load absorbing resistance, but this is not used, for the current generated is fed back into the line. Both dynamometers are controlled independently of each other, because of the individual field rheostats.

METHOD OF TEST

The motor, or driver, was first equipped with the desired pulley, and was brought up to the required speed. The torque scale was then balanced at zero reading, so that the power necessary to drive the motor, idling, need not be deducted from the power input of the belt. Direct output of the motor may now be measured, without correcting for any losses. The generator, or absorption machine, was balanced while at rest, so that any torque, measured during the time the generator was driven by the belt, was a function of the power delivered by the belt. By regulating zero settings in this manner all mechanical losses, such as brush friction, windage, bearing friction, etc., are automatically tared, because all of these forces tend to rock the dynamometer cradles, and are thus weighed on the torque arm.

About thirty feet of belt was used for test purposes, which, when wrapped around the pulleys, gave center distances of approximately 13 to 14 ft., depending on the pulley diameters.

The belt was first tested on 24-in. pulleys, and the running-in time to take out the stretch was about twenty-four hours. During the running-in period, the speed varied between 3100 and 3200 ft. per minute, at approximately 1 per cent slip and 480 lb. total tension.

At the end of this period, the actual test was begun by setting the tension at 480 lb., running between 3100 and 3200 ft. per minute on 24-in. pulleys and 1-per-cent slip for about 15 minutes, after which the load was dropped and speeds adjusted to obtain approximately 0.2-per-cent slip. The tension was then allowed to assume its own value during the entire test. By this procedure, the tension was always adjusted the same for every test, thus assuring more comparable results. This figure of 480 lb. is taken because it gives on a rubber belt an approximate value for T_1 (tension on the right side of the belt) of 23 lb. per in. per ply, since this value is chosen by some rubber belt men as the most economical tension at which to run a rubber belt.

The procedure of test then was to increase the slip by small increments, control the speed of belt between the desired limits, and allow the tension to assume whatever value it may. Slips were increased to the point where it was found difficult to definitely regulate them.

The first test was made at a speed of 3100 to 3200 ft. per minute on 24-in. pulleys, followed by a test at 4300 to 4500 ft. per minute. At the completion of the tests using 24-in. pulleys, these were taken off the dynamometers, and 18, 12, and 8-in. pulleys substituted successively.

It was not attempted to cover every range of speed, but to begin at a reasonable definite speed on one of the pulleys, and overlap that speed on the next size pulleys, until the range of pulleys was covered.

It might be well here to outline the pulley sizes and speeds:

PULLEY SIZE, IN.	SPEED, R. P. M.	LINEAL BELT SPEED, FT. PER MINUTE
24	500 ±	3100 to 3200
	700 ±	4300 to 4500
18	650 ±	3100 to 3200
	925 ±	4300 to 4500
12	650 ±	2000 to 2100
	1000 ±	3100 to 3200
8	525 ±	1100 to 1200
	950 ±	2000 to 2100

All pulleys were cast iron, 14 in. across the face, and crowned. The belt was a 4-in 4-ply belt taken from a regular run of production belts, and was spliced with a metallic fastener.

Nomenclature:

"Slip" has been used throughout this paper for the want of a better word, and because it has been popularly understood to mean the difference in speed of the driver and the driven pulleys. It is assumed, from previous work, that a difference in speed up to about 1 or 1½ per cent is mostly creep, and beyond that figure it is all slip. But for the sake of brevity, it has all been called slip.

T_1 is the tension on the tight side of the belt, and T_2 the tension on the slack side.

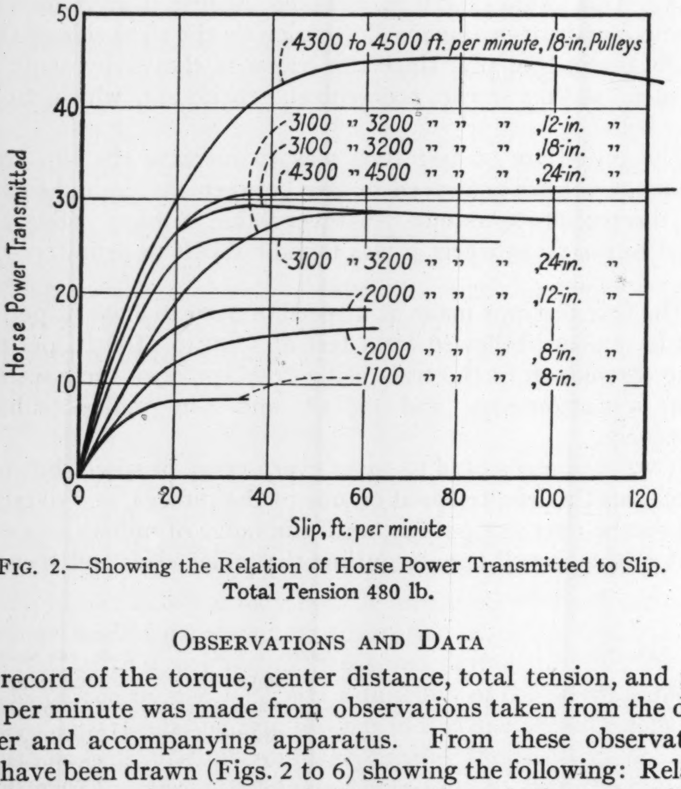

FIG. 2.—Showing the Relation of Horse Power Transmitted to Slip. Total Tension 480 lb.

OBSERVATIONS AND DATA

A record of the torque, center distance, total tension, and revolutions per minute was made from observations taken from the dynamometer and accompanying apparatus. From these observations, graphs have been drawn (Figs. 2 to 6) showing the following: Relation of horse power to percentage of slip; relation of slip to fraction of maximum belt tension turned into effective pull; relation of slip to the ratio of T_1 to T_2; and the relation of efficiency to horse power transmitted. Other data includes percentage stretch of belt, and tables. The lower strand of the belt tested was the tight side. The tests were conducted during the cooler months of the year, and the temperature of the test room averaged between 70 and 75° F., with prevailing humidity conditions.

DISCUSSION OF RESULTS

Relation of Horse Power to Slip in Feet per Minute:

It is a significant fact that the horse power a belt will transmit varies with the slip. As the slip increases, the horse power increases, not indefinitely, but within limits.

Consulting Fig. 2, it will be noted that in general, as the pulley sizes and speeds increase, the maximum slip in feet per minute increases. Slips were controllable up to about 3 per cent of the belt running speed; beyond that point, they were uncontrollable.

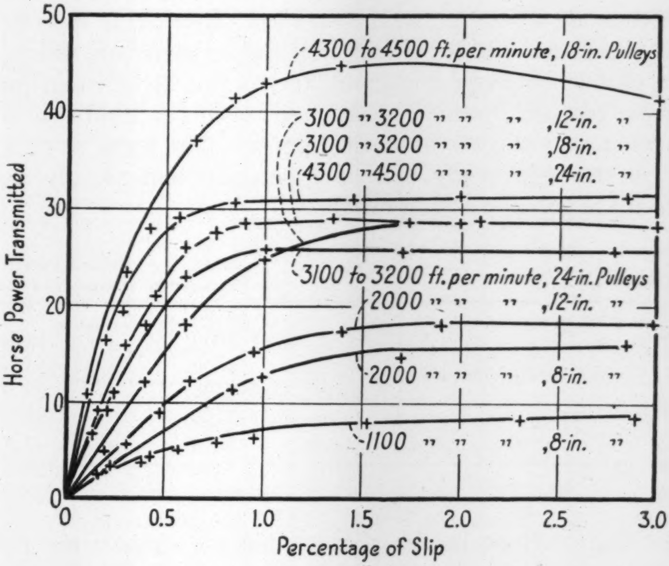

FIG. 3.—Showing the Relation of Horse Power Transmitted to Percentage of Slip. Total Tension 480 lb.

It is worthy of note that the horse power - slip curve of this belt is the characteristic curve of all rubber belts. That is, the slope is rather steep at first; it changes quickly at its peak; and from the peak on, it becomes parallel to the abscissa. A fact observed is that the belt transmits a maximum of power on 18-in. pulleys, and, at the same speed of the belt, drops off on 24-in. pulleys. Naturally, a greater amount of power will be transmitted at the higher speed on the same pulley, but the character of the curve will be the same. Again, less slip, in actual feet per minute, is required to transmit the same horse power, if either pulley size up to 18 in., or the lineal speed is increased.

Relation of Horse Power to Percentage of Slip:

Consulting Fig. 3, it may be seen that the slope of the horse power curve begins to drop off at about 1 to 1½ per cent slip. In ordinary practice, at this point, or just beyond it, the belt begins to squeak or squeal, and the operator begins to do something about it. In other words, something is wrong, and he either tightens the belt, or he may rebelt the machine. It is also true that excessive slips are beyond the limits of ordinary practice, and the performance characteristics that are of the greatest value are those at, or below, the 1-per-cent slip point. It is believed justifiable, therefore, to draw conclusions on the behavior and characteristics of belts, when operating below 1 per cent slip, and it is with these reasons in mind that we have chosen 1 per cent slip as the critical point. The horse powers transmitted by this 4-in. 4-ply belt at 1 per cent slip are given below; the speeds are given in round numbers:

PULLEY DIAMETER, IN.	SPEED, FT. PER MINUTE	HORSE POWER TRANSMITTED AT 1 PER CENT SLIP
8	1100	7.00
8	2000	12.50
12	2000	15.50
12	3100	25.00
18	3100	28.50
18	4300	42.75
24	3100	26.00
24	4300	31.00

The figures given in the above table are taken from points in Fig. 3.

The horse powers transmitted at ½ per cent slip are given below, and it is probable that the figures are nearer the average found in practice than those with the higher slip:

PULLEY SIZE, IN.	SPEED, FT. PER MINUTE	HORSE POWER TRANSMITTED AT ½ PER CENT SLIP
8	1100	5.0
8	2000	7.0
12	2000	9.5
12	3100	15.0
18	3100	22.0
18	4300	32.5
24	3100	20.0
24	4300	27.5

The maximum loads carried by the belt as taken from Figs. 2 and 3 are given below:

PULLEY SIZE, IN.	APPROXIMATE SPEED, FT. PER MINUTE	MAXIMUM HORSE POWER TRANSMITTED	APPROXIMATE SLIP, FT. PER MINUTE	APPROXIMATE SLIP, PER CENT
8.........	1100	8.5	35	2.9
8.........	2000	16.0	63	2.9
12.........	2000	18.0	62	3.0
12.........	3100	28.5	70	2.5
18.........	3100	29.0	40	1.5
18.........	4300	45.0	75	1.8
24.........	3100	25.5	34	1.1
24.........	4300	31.0	43	1.0

By interpolating between the curves of each pulley size for other pulleys and speeds, a very close approximation may be obtained of a desired horse power and its corresponding slip.

When considering horse power only at the speeds employed, the ideal pulley size for a 4-in. 4-ply Condor belt is 18 in. It is true, however, that 12-in. pulleys will transmit the same horse power as will 18-in. pulleys at 3100 to 3200 ft. per minute, but it is done at the expense of greater slip, which is not a desirable feature.

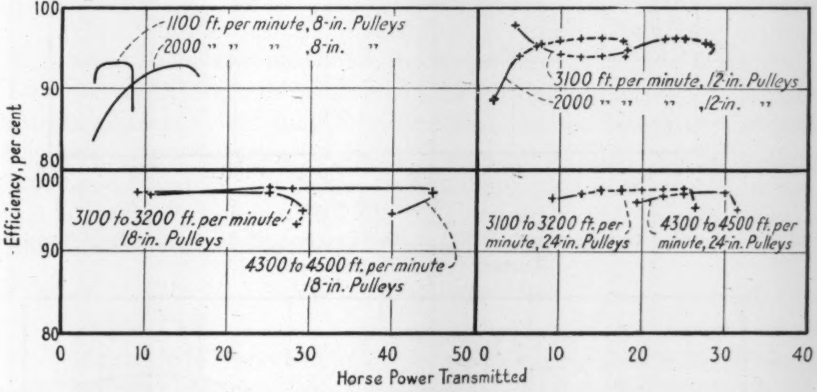

FIG. 4.—Showing the Relation of Efficiency to Horse Power Transmitted.

Even though a belt may be traveling at the same lineal speed on two different size pulleys, it may not transmit the same horse power, all other things being equal. A comparison of the 8 and 12-in. pulleys at 2000 ft. per minute proves this. The larger size pulleys transmit the higher horse power. Hence, if it is desired to increase the horse power of a drive, within its limits, keeping the lineal speed constant, it may be done by substituting a larger pulley. Another apparent fact which may be learned from these horse power-slip curves is that the same horse power may be transmitted by increasing pulley sizes and cutting down creep or slip, as the case may be.

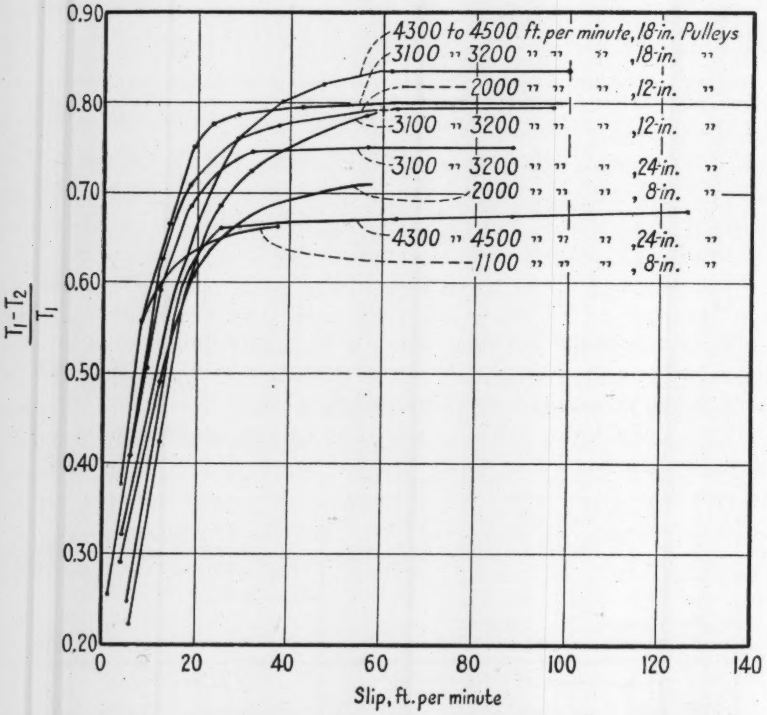

FIG. 5.—Showing the Relation of Slip to the Fraction of Maximum Belt Tension Turned Into Effective Pull.

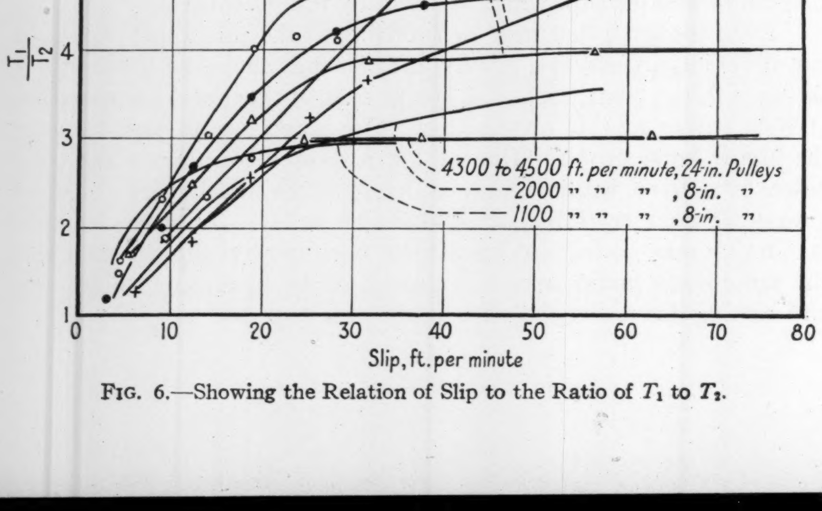

FIG. 6.—Showing the Relation of Slip to the Ratio of T_1 to T_2.

Relation of Efficiency to Horse Power Transmitted:

To get the full significance of these values, reference should be made to the curves in Fig. 4. A table showing the relations between the belts and their characteristics would be helpful in evaluating them:

PULLEY SIZE, IN.	SPEED, FT. PER MINUTE	MAXIMUM EFFICIENCY, PER CENT	HORSE POWER AT WHICH BELT ATTAINS MAXIMUM EFFICIENCY	SLIP AT WHICH BELT ATTAINS MAXIMUM EFFICIENCY, PER CENT	HORSE POWER AT WHICH BELT DROPS FROM MAXIMUM EFFICIENCY	SLIP AT WHICH BELT DROPS FROM MAXIMUM EFFICIENCY, PER CENT
8....	1100	93.0	5.0	0.500	8.0	0.800
8....	2000	93.0	13.0	0.975	14.5	1.250
12....	2000	96.5	11.0	0.575	17.0	1.300
12....	3100	96.5	4.5	0.150	25.0	1.250
18....	3100	97.5	9.0	0.150	26.0	0.675
18....	4300	97.5	10.5	0.100	44.5	2.200
24....	3100	97.5	15.0	0.275	26.0	1.250
24....	4300	97.0	25.0	0.250	30.5	0.800

When considering the advisability of using a belt, one is prone to consider only the maximum horse power the belt will transmit. To do so would seem to be an error, for a thing of paramount importance is efficiency. It may be noted that the maximum efficiency of this belt ranges between 93 and 97.5 per cent at horse powers ranging between 4.5 and 25. It should be noted also that in all cases but two, this is reached at slips of 0.5 per cent or under, and the efficiency is maintained over a wide range of horse powers.

Relation of Slip to Fraction of Maximum Belt Tension Turned Into Effective Pull:

This study is embodied in Fig. 5. The curves are similar in shape and form to the horse power-slip curves; that is, the slope of the curve up to about 1 per cent slip is a straight line; it then gradually rounds itself out and becomes horizontal. In other words, the practical fact shown by these curves is that as the speed increases, the ratio of effective pull (T_1–T_2) to tight side tension T_1 increases. It might be worth noting the ratio of (T_1–T_2) to T_1 at 1 per cent slip in the following table:

SPEED, FT. PER MINUTE	SLIP, FT. PER MINUTE AT 1 PER CENT SLIP	PULLEY SIZE, IN.	$\frac{T_1-T_2}{T_1}$
1100........................	11	8	0.590
2000........................	20	8	0.615
2000........................	20	12	0.720
3100........................	31	12	0.625
3100........................	31	18	0.790
4300........................	43	18	0.810
3100........................	31	24	0.745
4300........................	43	24	0.670

The average value of the above ratios at 1 per cent slip is about 0.7, and ranges from 0.59 on 8-in. pulleys at 1100 ft. per minute to 0.81 on 18-in. pulleys at 4300 to 4500 ft. per minute. In other words, the fraction of maximum tension converted into effective pull at 1-per-cent slip is about 0.7. There are greater ratios than 0.7, but they are at greater slips.

Relation of the Ratio T_1/T_2 *to Slip:*

This relation is shown in Fig. 6. Considering again the point of 1 per cent slip, a table showing this relation is given below:

SPEED, FT. PER MINUTE	SLIP, FT. PER MINUTE AT 1 PER CENT SLIP	PULLEY SIZE, IN.	$\frac{T_1}{T_2}$
1100	11	8	2.50
2000	20	8	2.65
2000	20	12	3.55
3100	31	12	3.55
3100	31	18	4.80
4300	43	18	5.40
3100	31	24	3.85
4300	43	24	3.00

These figures are very interesting and indicate that the ratio T_1/T_2 varies or increases as either pulley sizes or speeds increase, or both. Some published data give a definite ratio of T_1/T_2 equal to $\frac{7}{3}$, but the above results seem to differ from this value.

Stretch:

In conjunction with the above tests, stretch data were collected. The stretch figures given are the maximum stretches recorded during 6 separate performance tests. The original length of the belt was 30 ft. before it was put on the apparatus. With fasteners attached it measured 30 ft. $\frac{7}{16}$ in. All stretch measurements were based on the original length of 30 ft. $\frac{7}{16}$ in.

TEST	STRETCH, PER CENT
No. 1	2.1
No. 2	2.1
No. 3	2.1
No. 4	1.6
No. 5	1.75
No. 6	1.6

At the completion of the tests, the belts were taken off the pulleys and allowed to remain loosely wound in the testing room for a period of 1 week, after which time they were remeasured. It was found that the belts had received a permanent set of about 0.8 per cent.

Strength:

Other belts taken from the same lot manufactured at the same time that the above belt was manufactured had a strength equal to about 5600 lb. per sq. in.

CONCLUSIONS

The above work has verified the work of others that the horse power - slip curves of a rubber belt have a definite shape. Analyzing these curves, the smaller pulleys at low lineal speeds give a relatively flat curve. As the pulley sizes increase, together with the speed, the curve becomes steeper and the shape of the curve changes. The slope is quite steep up to 1 to 1½ per cent slip; it then flattens out and becomes parallel to the slip axis. This is quite noticeable in the curves of the 18-in. pulleys, when compared to the 8 and 12-in. pulleys. In other words, an outstanding point is that the horse-power curve of a rubber belt reaches a maximum and regardless of the slip beyond that point, the horse power neither increases nor decreases.

A point brought out in the collection of the data is that as the slip of a belt increases, the total tension in the belt increases. As an example, at 1 per cent slip the total tension averaged 480 lb., but in some cases at 3 per cent slip the tension rose to 500 lb.

From Fig. 2 we gather that the horse power transmitted may be increased and the actual slip in feet per minute decreased by increasing the pulley size, or by increasing the linear speed on the same pulley size.

Up to the 1-per-cent slip point there is an increase in power transmitted as pulley sizes increase and speeds increase up to and including 18-in. pulleys. The loads transmitted seem to drop off on the 24-in. pulleys.

The efficiency curves of the 8-in. pulleys are quite irregular; they begin to straighten out for the 12-in. pulleys and follow nearly a straight line for the 18 and 24-in. pulleys. Except for the 8-in., the efficiency of this 4-in. 4-ply belt will average between 95 and 97 per cent.

The ratio of maximum belt tension converted into effective pull when charted with slip in feet per minute, produces a curve exactly like the horse power - slip curves. In other words, as the pulley sizes and speeds increase, the ratio increases, reaching a maximum of 0.835 on 18-in. pulleys at a speed of 4300 to 4500 ft. per minute. The ratio drops off on 24-in. pulleys.

The general shape of the T_1/T_2 curve when plotted against slip also has the same general shape as the previous curves. In general, it might be said that the ratio of T_1/T_2 for a 4-in. 4-ply belt under the above test conditions will lie between 3 and 5, with an exception made for 18-in. pulleys at 4300 to 4500 ft. per minute.

Although relatively high horse powers may be transmitted over 24-in. pulleys under conditions outlined above, the foregoing tests indicate that the most economical pulley sizes over which to run this 4-in. 4-ply rubber belt are 12 to 18 in.

It should be borne in mind also that the data given in this paper are different and farther reaching than those given in the Belt Manufacturers Handbook. In the Handbook, recommendations are made with a consideration for the life of the belt, and are much more conservative than the data given above.

DISCUSSION

Mr. V. A. Cosler[1] (*presented in written form*).—Mr. Skane concludes from his tests that of the 8, 12, 18 and 24-in. pulleys, the 18-in. pulley will transmit the most power, other conditions being the same. The question arises as to why the 24-in. pulley should not transmit as much or more power than the 18-in. pulley. There is no theory or explanation given for the reason for this drop in power on the 24-in. pulley, and nothing is apparent from the data given. In the absence of a possible explanation or theory, we believe that the tests should be extended to at least one pulley size greater than 24 in. in order to prove that the curve of power *versus* pulley size actually reaches a peak around 18 in. for the belt tested. Otherwise it may be suspected that an unknown variable in testing may have thrown the 24-in. pulley test out of line. In this connection, we understand that the test on the 24-in. pulleys was the first test run after the 24-hour breaking-in period. It may be that the belt was not completely broken in during this first test. It seems that in further tests of this nature it would be well to use a wider belt. The wider belt would tend to conform to the crown of the pulley more readily than the narrow belt.

Mr. Skane's method of setting the tension at the start of each test and then making no further adjustment during the test, while a suitable method for obtaining comparable results between different tests, does not seem to give a proper basis for drawing conclusions for judging actual service applications. Figures given below will illustrate this point. It seems that the data would be more valuable if a record were included of the actual total tension on the belt for each reading.

Referring to Fig. 2 of the paper, take the point at which the belt at 4300 to 4500 ft. per minute on the 18-in. pulleys transmits 30 hp. The slip at this point is 20.5 ft. per minute; at the same slip and at the same speed the belt transmits 26.5 hp. on the 24-in. pulleys. However, taking 480 lb. as the total tension in both cases, the tension on the tight side on the 18-in. pulleys amounts to 22.2 lb. per ply inch, while the tension on the tight side on the 24-in. pulley is 21.3 lb. At the same slip the belt is transmitting less power on the 24-in. pulleys, but at the same time it is running under a lower maximum stress. In a practical application under such conditions the initial tension on the 24-in. pulleys could be increased, giving more horsepower without increasing the maximum stress on the belt, and at the same time retaining the advantage of longer life on the large pulleys.

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[1] Technical Superintendent, Mechanical Division, The B. F. Goodrich Co., Akron, Ohio.

Assuming that the ratio of T_1 to T_2 remains the same, if the belt tension on the 24-in. pulleys is increased to 22.2 lb. per ply inch on the tight side, equal to that on the 18-in. pulley when transmitting 30 hp., the horsepower will be increased from 26.5 to 27.4. While this does not equal the power on the 18-in. pulley, it indicates that the best pulley size for power transmission of a given belt cannot be determined without taking into account the proper total tension on the belt. If the tension on the 24-in. pulleys is increased to 24.2 lb. per ply inch on the tight side, giving a total tension on 546 lb. the belt should transmit 30 hp. The value 24.2 lb. per ply inch is still a very conservative figure.

Mr. Skane states in his discussion that "It is a significant fact that the horse power a belt will transmit varies with the slip. As the slip increases, the horse power increases, not indefinitely, but within limits." It would appear from this statement that the slip was considered as the independent variable and the horse power the dependent variable. We believe that the reverse of this is true, that at a given total tension and with other conditions equal, the amount of slip will depend on the load which is applied to the belt. In other words, the slip increases as a result of a horse power increase.

MR. J. E. SKANE[1] (*author's closure by letter*).—In answer to Mr. Cosler's suggestion that a larger pulley than the 24 in. should be used, in order to prove that the curve of power *versus* pulley size actually reaches a peak around 18 in. for the belt tested, it may be stated that the 24-in. pulley was the largest we had in our test equipment at that time.

We have as yet not been able to evolve a reason to fit the data that the 4-in., 4-ply belt tested, transmitted its greatest power on the 18-in. pulleys. It is possible, however, with a given length of belt and tension, there is a greater sag on the slack side, consequently a greater arc of contact on the 18-in. pulleys than on the 24-in. pulleys. It is regretted that these observations were not taken during the gathering of the data.

We cannot agree with Mr. Cosler's explanation that the belt may not have been completely broken in. The belt was run in for over 50 hours before testing, and, by the way, because of the difference in power transmitted between the 18-in. and 24-in. pulleys, the 24-in.

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pulleys were put on the dynamometer again after the completion of the tests on the 18-in. pulleys, and the tests found to check. Furthermore, Mr. Norman in his work has shown that a rubber belt begins to transmit its full load when new and at the start of its test. In our work we have found that after 50 hours running-in period, a belt transmits its full load.

Referring to the method of setting the tension, we felt that the method employed is the nearest approach to that used in actual practice. In other words, when a belt is applied to two pulleys on two fixed lines of shafting, its initial tension is adjusted or set when the belt is wrapped around the pulleys; and its length and naturally its tension cannot be changed until the belt is taken off again and cut to take up whatever the belt has stretched.

Again, in actual practice, belts are applied at a definite cut length for all pulleys and are not varied for different sizes of pulleys. It was actual practice that we had in mind that prompted us to apply the belts at a definite tension and to allow them to assume their own tensions under varying loads. It is quite evident also in observing the tension behavior of a belt on a dynamometer that, as higher loads are applied to the belt, higher total tensions are noted on the tension scale. This point was discussed in a letter to the writer by Professor Norman of Ohio State University in an analagous case on a leather belt when he said, "It is set forth that as the slip of a leather belt increases, the pull on the shafts increases. This is undoubtedly true, especially if the belt was put on fairly slack to begin with. It should be emphasized, however, that in this case the power transmitted goes up with the slip also, so that the increased pull on the shafts is legitimate and unavoidable, since it is simply a reaction to the pull transmitted."

In answer to the last point, it was stated under "Nomenclature" page 932, that for the sake of brevity, creep and what little slip enters into the tests had all been called slip. It is true that at lower percentages of creep—2 per cent—the tight-side tension is low and as the belt begins to transmit a greater load, a greater tight-side tension accumulates, and a greater creep occurs. The statement that "As the slip increases, the horse power increases" was made merely to show that as one, the horse power, increases, the other, the slip, increased up to a certain point, when there is no increase of power transmitted with increased slips.

STRETCH IN RUBBER TRANSMISSION BELTING

By C. W. Staacke[1]

Synopsis

To give satisfactory service to the consumer, a transmission belt must be practically free from inelastic or permanent stretch. The investigations set forth in this paper were made to determine the proper amount of inelastic stretch to remove from the belting during the vulcanization process when using a given fabric.

Eight identical samples of 6-in. 4-ply belting were given amounts of stretch varying from zero to 11.6 per cent. The following comparative tests were then made:

Stress-strain (before and after dynamometer test); flexing; ply adhesion (before and after dynamometer test); hysteresis and set; and dynamometer.

The conclusions drawn from this work are:

1. The results indicate that each test method is an important aid in determining the amount that transmission belting should be stretched during vulcanization.
2. This testing procedure can be used to determine the percentage of stretch to remove from any fabric used in the manufacture of rubber transmission belting.
3. In case of this particular construction, a belt stretched between 7 and 8 per cent during vulcanization will render satisfactory service.

Transmission belting is used for the economical transmission of power from one machine to another. In addition, the belting acts as either a speed reducer or accelerator and as a flexible coupling. It absorbs overloads by stretching momentarily and allowing the belting to slip on the pulleys, thus protecting the machinery and the belt.

In order to perform the above duties a good transmission belt must have the folowing characteristics:

1. Maximum strength with minimum thickness;
2. Ability to withstand flexing over small pulleys at high speed and not break down from stress from the heat caused by flexing, or from the heat generated by slipping;
3. A high coefficient of friction against the rim of the pulleys in order to transmit maximum power with minimum slipping;
4. Freedom from inelastic stretch; and
5. The proper amount of elastic stretch.

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[1] Mechanical Goods Technical Dept., The B. F. Goodrich Co., Akron, Ohio.

Transmission belts are made from a great many different substances such as leather, balata-treated fabric, camel's hair, stitched canvas and so-called rubber belting. Rubber belting is made from plies of cotton fabric properly frictioned with a rubber compound and then vulcanized into a finished belt. Of the various kinds of belts listed, rubber belt gives the least trouble from stretching in service, for the reason that most of the inelastic stretch can be removed from the belting by placing it under tension during the vulcanization process.

This paper covers experimental work done in an effort to determine the proper amount of stretch which should be removed from rubber belting during vulcanization. The ideal belt would have all of the inelastic stretch removed from it, leaving only the elastic stretch.[1]

TABLE I.—RESULTS OF STRETCH TESTS ON RUBBER BELTING.

STRETCH IN 25-FT. PRESS LENGTH, IN.	SHRINKAGE AFTER CURE, IN.	PERCENTAGE STRETCH		FINAL WIDTH, IN.	DECREASE IN WIDTH, IN.
		INITIAL	FINAL		
0	1.25	0.00	0.79	6.125	0.00
5	2.00	1.66	0.40	6.125	0.00
10	2.75	3.33	1.59	6.100	0.025
15	3.37	4.99	2.86	6.100	0.025
20	2.87	6.66	4.84	6.080	0.045
25	3.62	8.33	6.02	6.060	0.065
30	3.50	9.98	7.77	6.040	0.085
35	3.87	11.65	9.21	6.010	0.115

The belting used in this work was made from a special hard-woven belt duck approximately 33 oz. per yd. on a 42-in. width. The duck was processed in the usual manner and made into belting for test purposes.

CONSTRUCTION AND TEST OF SAMPLES

The samples of belting used for tests under the above heading were cut from a 4-ply slab of uncured belting. Eight samples were cut simultaneously on a fabric-cutting machine, each sample being cut $6\frac{1}{8}$ in. wide. These samples were then cured in a $12\frac{1}{2}$-ft. press, four at a time. The amount of stretch given each sample was carefully checked and the following observations and tests were made on the resulting samples.

Recovery and Final Width After Removing from Press:

Marks were placed on each sample at both ends of the press plate, and the distance between these marks measured after the belt

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[1] "Inelastic stretch" is the permanent stretch which occurs when the belt is under tension or load. "Elastic stretch" is that stretch which occurs when the belt is placed under tension or load, but which is recovered as soon as the tension or load is released.

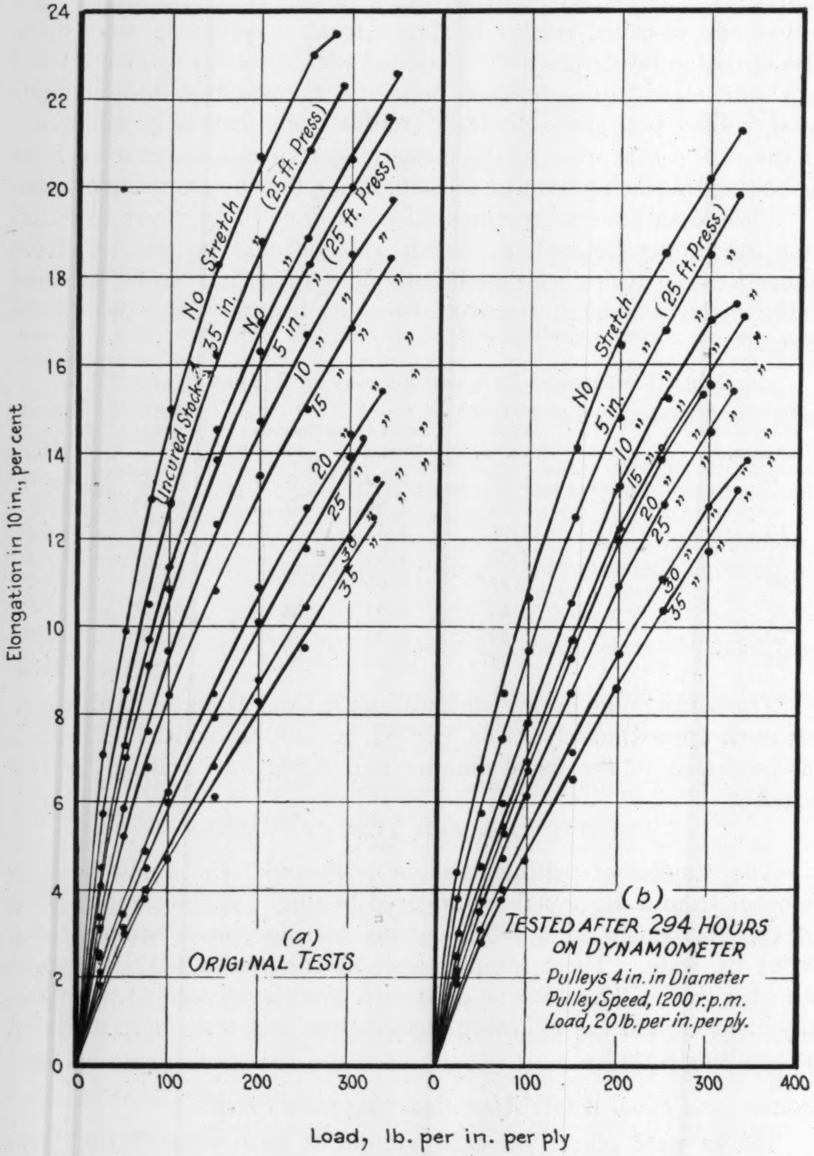

FIG. 1.—Stress-Strain Curves of 6-in. 4-ply Special Belting.

was removed from press and allowed to cool, in order to determine the percentage of the initial stretch which was held. The total length of the press plate was 13 ft. 2 in. The average width of the finished belt was also measured. Initial width of uncured samples was 6⅛ in. The results are as shown in Table I.

Stress-Strain Tests:

Stress-strain tests were made in a 50,000-lb. Riehle machine at a jaw separation speed of 0.6 in. per minute. Elongation was measured on a 10-in. section. Tests were made before and after the dynamometer test described later. A test was also made on the uncured stock cut from the portion of the samples located between the stretching clamp and the press plates during cure. During the cure the clamp was not released after closing the press, so that the stretch was held in this part of the belting during the entire time of the cure.

TABLE II.—FRICTION TESTS.

STRETCH IN 25-FT. PRESS LENGTH, IN.	FRICTION PULL, LB.			
	FIRST PLY	SECOND PLY	THIRD PLY	AVERAGE
	ORIGINAL SAMPLES			
0	29	26½	25½	27.0
5	23¾	24½	18¼	22.2
10	24	28	22½	24.8
15	29	25	24¼	26.1
20	23	27	18½	22.8
25	31¼	22½	25¾	26.5
30	29	24	26¼	26.4
35	21½	22¼	18½	20.8
	AFTER 294 HOURS ON DYNAMOMETER			
0	17¾	23	24¼	21.7
5	27½	23½	13¾	21.6
10	22	20½	17¾	20.1
15	19	25¼	17¾	20.7
20	30	22¼	22¼	24.8
25	22¾	22½	24¼	23.1
30	26¼	24½	22	24.2
35	23¼	21	20¾	21.7

NOTE.—The average friction pull after the dynamometer test showed a greater decrease on samples stretched 15 in. and under than on those stretched 20 in. and over.

Stress-strain characteristics are shown in Figs. 1 (*a*) and (*b*). Figure 1 (*a*) shows the original tests and Fig. 1 (*b*) the tests after the belt had run 294 hours on the dynamometer. The tests on the two uncured samples tested are marked "uncured stock."

The elongation of samples stretched 15 in. and under was less after the dynamometer test than before, while that of samples given 20 in. of stretch and over was greater. This is an indication that the samples given the greater amounts of stretch had better recovery or elastic properties than those stretched lesser amounts.

Flexing Tests:

Samples 1 in. wide and 8¼ in. long were tested in a Scott flexing machine designed by the United States Rubber Co. The testing hub of the machine is 1¼ in. in diameter. A load of 100 lb. was placed on each sample and the machine driven at a speed of 165 strokes per minute. Ten samples of each belt were tested. Tests on each sample were continued until ply separation extended completely across the sample.

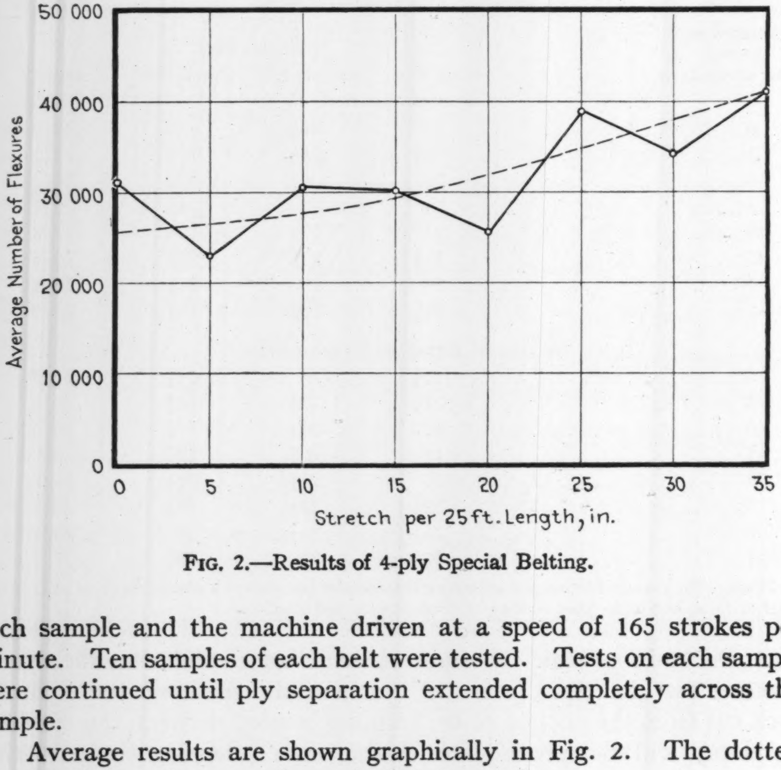

FIG. 2.—Results of 4-ply Special Belting.

Average results are shown graphically in Fig. 2. The dotted curve indicates the general trend of these results.

Friction Tests:

Test samples 1 in. wide were cut transversely from the belts and tested for ply adhesion in a Cooey testing machine. Plies were separated at the rate of 1 in. per minute. Tests were made before and after the dynamometer test. The results are given in Table II.

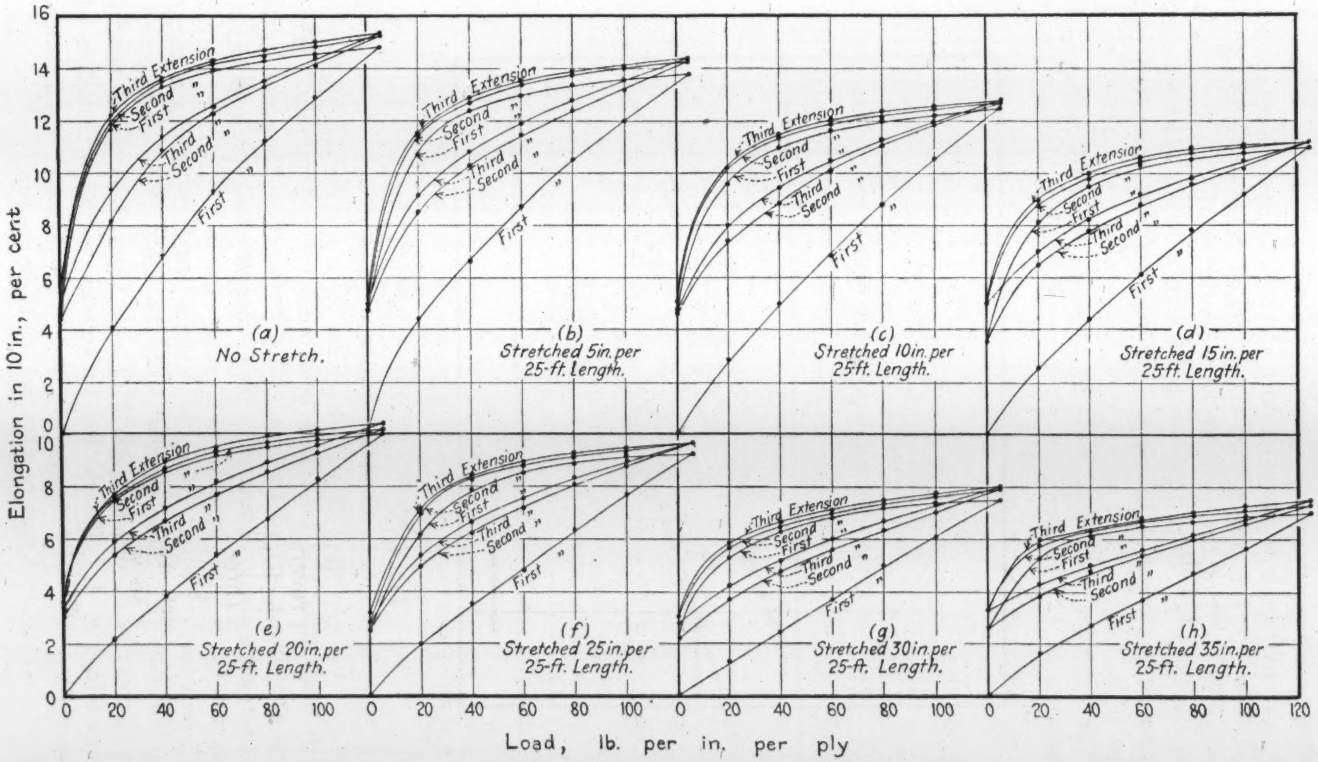

FIG. 3.—Results of Hysteresis Tests of 6-in. 4-ply Special Belting.

Hysteresis Tests:

Under hysteresis is reported both the regular hysteresis tests and the set tests, for the reason that the principal value of these tests is the determination of the percentage recovery, or the elastic properties of the belting. Both tests were made in a 500-lb. Riehle testing machine on a sample 1 in. wide. Elongation was measured in a section 10 in. long.

The hysteresis test was made by applying specified loads up to a maximum of 125 lb. per inch per ply and reading the elongation at each load after the load had been held for one minute. This process was then reversed and elongation obtained at the same loads while decreasing the load to zero. This procedure was repeated twice, making a total of three extensions on each sample.

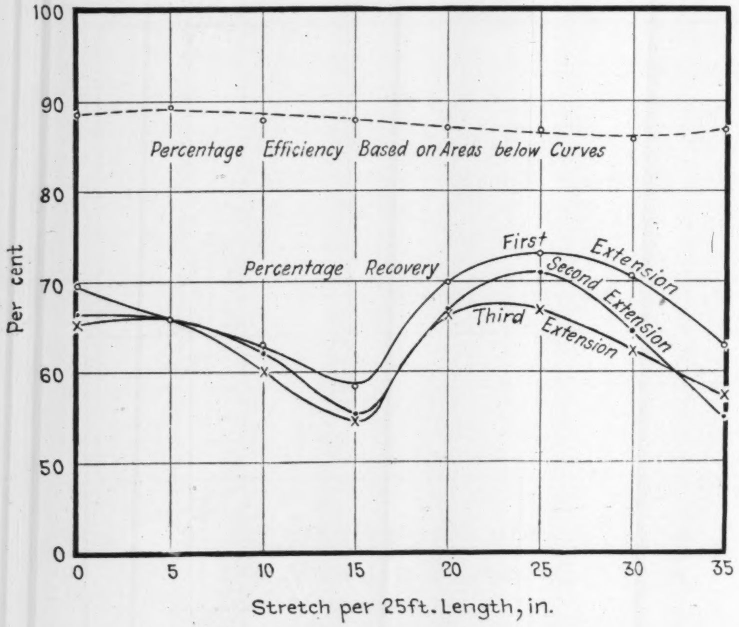

FIG. 4.—Combined Results of Fig. 3.

Curves were plotted from the results obtained and the areas subtended between these curves and the axes were determined. These curves are shown in Figs. 3 (*a*) to (*h*). Combined results are shown in Fig. 4. The dotted curve was plotted with values of efficiency determined by means of the areas obtained. Apparently no especial significance can be attached to these results.

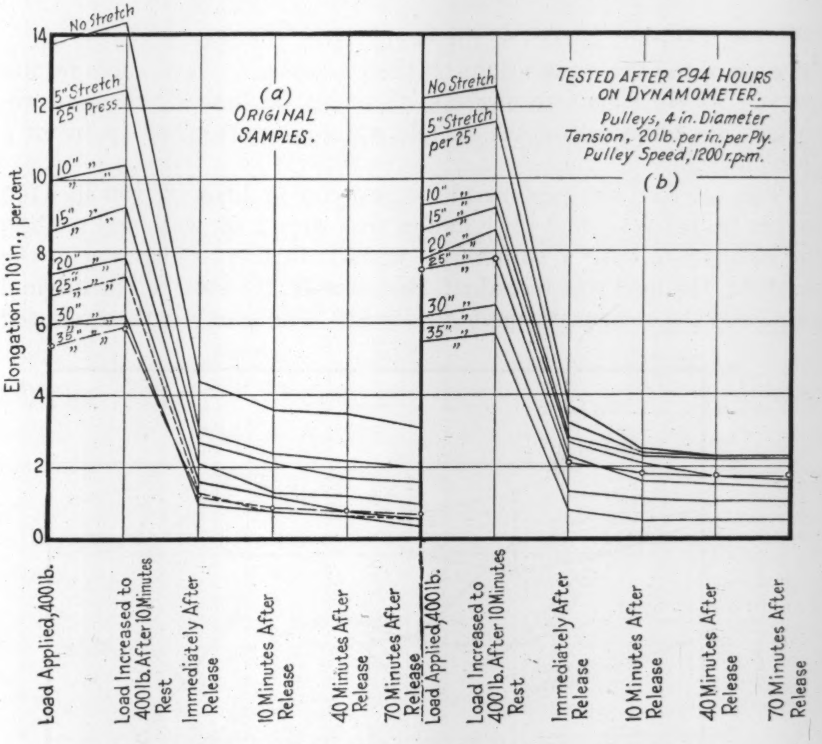

FIG. 5.—Results of Set Tests of 6-in. 4-ply Special Belting.
Test specimens 1 in. wide.

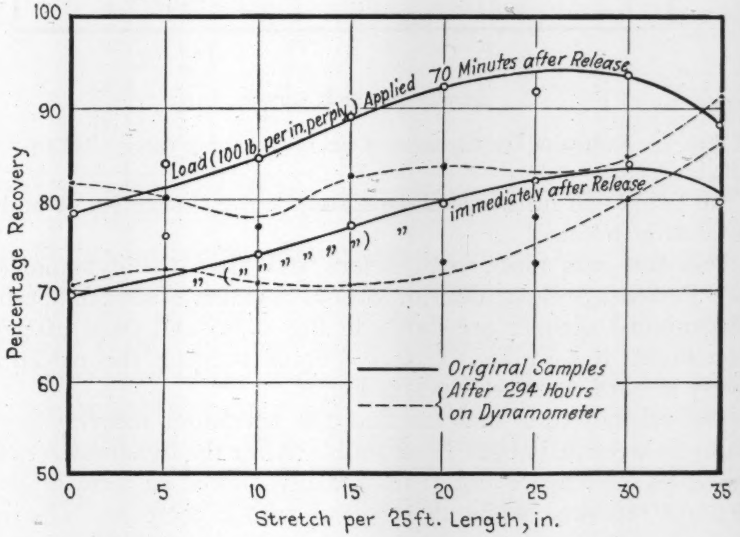

FIG. 6.—Results of Set Tests of 6-in. 4-ply Special Transmission Belting.
Test specimens 1 in. wide.

The solid line curves of Fig. 4 represent the percentage recovery for each of the three extensions on these samples. While these results are not as consistent throughout as might be desired, the best recovery was obtained on the sample which was stretched 25 in. in a 25-ft. length.

The set test was performed by applying a load of 400 lb. (100 lb. per in. per ply) on 4-ply samples that were 1 in. wide and reading the elongation. After 10 minutes without further adjustment of the machine, the load was recorded; then it was increased to the original value and the elongation again measured. The load was then released and the elongation measured immediately and again at 10, 40 and 70 minutes after release.

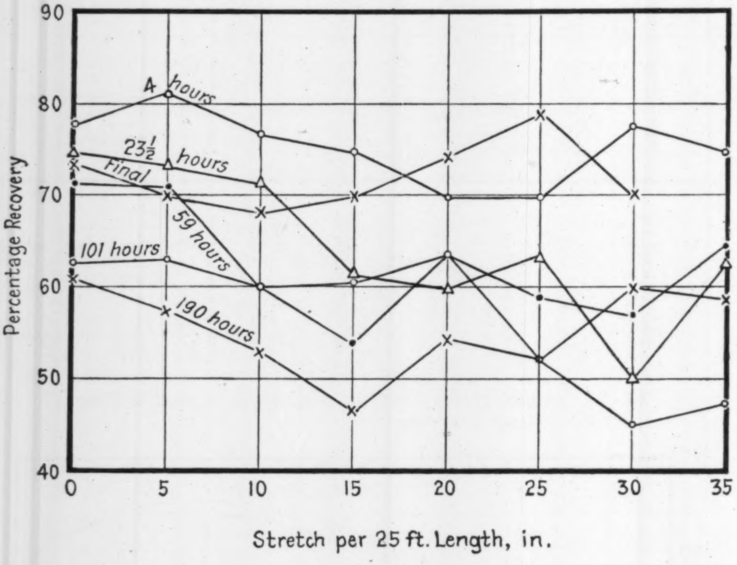

FIG. 7.—Results of Dynamometer Tests of 6-in. 4-ply Special Belting.

This test was made both before and after the dynamometer tests. Percentage elongation for various amounts of stretch obtained on the original samples are shown in Fig. 5 (*a*) and those after the dynamometer test in Fig. 5 (*b*). Curves showing the percentage recovery in both cases are given in Fig. 6.

The original tests indicate that the maximum recovery occurs on samples stretched about 25 or 30 in. After the dynamometer test the samples stretched 0 and 35 in. actually showed an increase in the percentage recovery, while all others showed a decrease. Contrary to expectations the largest decrease occurred on the sample which had been stretched 25 in.

Dynamometer Test:

A 5-ft. section was cut from each sample and the eight sections spliced together with Alligator fasteners, making a belt 40 ft. in length. This belt was tested on 4-in. pulleys at a speed of 1200 r.p.m. The tension on the belt was maintained at a constant value of 20 lb. per in. per ply throughout the entire test. This gave a total tension of 480 lb. in each strand of belt. The elongation on a 3-ft. length of each sample was measured at intervals during the test, both under tension and immediately after releasing the tension.

TABLE III.—RESULTS OF DYNAMOMETER TESTS.

Diameter of pulleys, 4 in. Speed, 1200 r.p.m. Tension, 20 lb. per in. per ply.

Stretch in 25 ft., in.	Hours Tested	Percentage Elongation in 3-ft. Section		Percentage Recovery	Stretch in 25 ft., in.	Hours Tested	Percentage Elongation in 3-ft. Section		Percentage Recovery
		Under Tension	Tension Released				Under Tension	Tension Released	
0	4	6.00	1.33	77.8	20	4	3.33	1.00	70.0
	8	6.33	1.33	79.0		8	3.33	1.00	70.0
	23.5	6.67	1.67	75.0		23.5	3.33	1.33	60.0
	59	7.00	2.00	71.5		59	3.67	1.33	63.6
	101	7.17	2.67	62.8		101	3.67	1.33	63.6
	190	7.67	3.00	60.9		190	3.67	1.67	54.5
Final	...	....	2.03	73.5	Final	...	....	0.93	74.5
5	4	5.33	1.00	81.3	25	4	3.33	1.00	70.0
	8	5.67	1.00	82.4		8	3.33	1.00	70.0
	23.5	5.67	1.15	73.5		23.5	3.67	1.33	63.6
	59	6.33	1.83	71.1		59	3.67	1.50	59.0
	101	6.33	2.33	63.2		101	3.83	1.83	52.2
	190	6.67	2.83	57.5		190	3.83	1.83	52.2
Final	...	....	2.00	70.0	Final	...	....	0.80	79.1
10	4	4.33	1.00	77.0	30	4	3.00	0.07	77.8
	8	4.67	1.00	78.6		8	3.00	1.33	55.5
	23.5	4.67	1.33	71.5		23.5	3.00	1.50	50.0
	59	5.00	2.00	60.0		59	3.17	1.33	57.9
	101	5.00	2.00	60.0		101	3.33	1.83	45.0
	190	5.33	2.50	53.1		190	3.33	1.33	60.0
Final	...	....	1.70	68.2	Final	...	....	1.00	70.0
15	4	4.00	1.00	75.0	35	4	2.66	0.67	75.0
	8	4.00	1.33	66.7		8	2.66	1.00	62.5
	23.5	4.33	1.67	61.5		23.5	2.66	1.00	62.5
	59	4.33	2.00	53.8		59	2.83	1.00	64.7
	101	4.67	1.83	60.7		101	2.83	1.50	47.1
	190	4.67	2.50	46.4		190	2.83	1.17	58.8
Final	...	....	1.40	70.0	Final	...	....	....	....

NOTE.—Belt was run a total of 294 hours. Final values of elongation were taken about 48 hours after the completion of the tests and should, therefore, represent absolute permanent set.

Curves showing the percentage recovery of the various samples after release are shown in Fig. 7. Readings of recovery for the final curve were taken about 48 hours after completion of the test. Readings for the other curves were taken as soon after release of the tension as possible. These curves are somewhat irregular, probably due to a variation in the order in which the readings were taken on the different samples.

The test was discontinued at the end of 294 hours when the sample which had been stretched 35 in. had been shortened to such an extent by ply separation and replacement of fasteners that no further readings of the elongation could be taken. Final examination showed more or less ply separation on all samples, starting at the fasteners in every case. The samples which had been stretched the least appeared to hold the fasteners for a greater length of time than those which had been given more stretch.

The following are comparative results[1] of the tests:

STRETCH IN 25-FT. LENGTH, IN.	NUMBER OF TIMES FASTENERS PULLED OUT	FINAL LENGTH OF SAMPLE, FT.	PLY SEPARATION AT COMPLETION OF TEST, IN.
0	2	4.93	7
5	2	4.77	7
10	0	4.9	2
15	0	4.9	7
20	3	4.05	5
25	3	4.44	6
30	4	4.18	22
35	5	3.55	4

GENERAL CONCLUSIONS

The preceding tests were all made in an effort to find the proper amount of stretch which should be given a belt made from a specific fabric to enable it to give the maximum amount of trouble-free life in transmission service. At first glance, the results obtained in the dynamometer test seem to indicate that belting stretched 10 or 15 in. will probably give just as good service as that stretched a greater amount. From the standpoint of stretch, however, experience has shown that belting which stretches 4 per cent or more will give rise to complaints on installations where a limited amount of take-up is available. It will also cause a great many shut-downs to take up the belt and there will be a tendency to stretch enough under each little overload to cause slipping until the take-up is run out or the belt shortened.

As stated under "Dynamometer Test," the samples which were stretched 15 in. or under gave less trouble with fasteners and ply separation than those stretched 20 in. or more. The ply separation in every case started at the fastener, the outer ply breaking at this point and separation developing as a result. The indications are, therefore, that the greater the amount of stretch removed from the belting during cure, the more tendency there will be for ply separation to go the entire length of the belt if it is once started. This can probably be accounted for by the fact that in passing over the pulley the outer ply must stretch to a greater extent than the plies nearer the pulley and, therefore, must support a greater portion of the total tension than the other plies. This variation in the tension on the different plies of the belt is probably less on the belt which had been stretched a small amount than on the belt which had been stretched more, due to the greater amount of flexibility in the former. The latter, then, breaks more quickly at the fastener and ply separation develops.

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[1] Complete results of this test are given in Table III.

In spite of the fact that the samples which were stretched the most showed the greater tendency to break at the fasteners, as well as for the plies to separate, these samples showed a smaller average decrease in friction pull after the dynamometer test than the samples with less stretch. This is a verification of the theory that a belt which stretches a large amount in service will show a more rapid breakdown of the friction than one which stretches a lesser amount, due to the fact that the friction is working under a higher tension. The flexing test results as shown in Fig. 3 also bear out this opinion. In this test, where fasteners and ply separation are factors which do not enter, the best results were obtained on the samples which were stretched the most.

Apparently, therefore, on the installation where little or no difficulty is to be expected with fasteners, the belt with the greater amount of stretch removed should give the more satisfactory results. While the differences indicated by the tests made are not very great, and on this basis alone any of the belts tested should prove satisfactory on an installation where a sufficient allowance is made for take-up, there is a possibility that the belt with the least amount of stretch removed from it during vulcanization would show in service the effects of aging more rapidly because of the greater tension under which the friction is operating. The tests did not cover a sufficient period of time to be affected by aging.

In the above discussion samples tested have been, in a general way, divided into two groups; those receiving a small amount of stretch as compared with those receiving a greater amount of stretch in the press. The former group consisting of samples stretched 15 in. or less is compared with the group stretched 20 to 35 in. It is concluded that for the average installation the latter group would be more satisfactory. The question remains as to which of these four samples most nearly approaches the ideal conditions of stretch.

A study of the stress-strain results, set tests and stretch in the dynamometer tests indicates that comparatively little advantage is gained in going above a stretch of 25 in. in 25 ft. of length. In most cases the percentage recovery, as indicated by the hysteresis test, the set test and the dynamometer test, is highest at approximately 25-in. stretch. Samples stretched more than this amount show a sharp decline in the percentage recovery, indicating that possibly the fabric has been subjected to an undue strain.

It seems conclusive, therefore, from the foregoing that a stretch of 25 in. in a 25-ft. length, or 1 in. per foot of length, is the most satisfactory amount to remove from this grade of belting during the vulcanization process.

Acknowledgment.—The author wishes to acknowledge the assistance given him by Mr. S. R. Reimel, in following the testing work and preparing the tables and graphs used in this paper.

SERVICE TESTS ON RUBBER BELTS

By E. G. Kimmich[1]

Synopsis

The paper gives results of extensive tests on rubber belting to determine the relative influence of various service conditions on the time that a belt will resist ply separation.

Various combinations of pulley diameters, tensions, belt speeds and thicknesses were used. The test belts were applied on two pulleys of equal size under controlled tension, and run until ply separation took place. The time required to separate the plies is given in a mathematical expression based on these tests. Some representative parts of the original data are given in the form of graphs which also include curves to show the close agreement between data and formula.

It was found that the relative ply-separating influence of the factors studied could be determined with equal accuracy with or without transmission of power. Because of the greater simplicity most of the tests were run without power transmission.

The tests reveal that the influence of several of the factors upon the service obtainable from a belt is much larger than usually considered. In fact, while the belting manufacturer may improve the belt resistance to ply separation by several times as has been accomplished in recent years, it is shown that the user of the belting has it within his power to increase or decrease the severity of the belt installation by much larger amounts by his selection of pulley sizes, tensions, number of plies and belt speeds.

Introduction

The tests here described were undertaken with the object of determining the effect of various factors in rubber-belt installations on the length of time that belts will operate without ply separation.

The cause of final removal of a belt from service is, of course, not always ply separation, but the breaking down of the adhesion between the plies has in a sufficient number of instances been the cause of removal to justify an extensive study under conditions approximating actual use in service.

The tests which were made include investigations of the ply-separating influence of pulley diameters, unit tensions, the number of plies, belt speeds, and combinations of these variables. The tests also include comparisons of the influence of these variables while transmitting power, with their influence with the belts running idle.

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[1] Development Department, The Goodyear Tire and Rubber Co., Akron, Ohio.

TEST METHODS

The power transmission tests were made on a 75-h-p. dynamometer of conventional type.

The tests without power transmission were made on a multiple unit machine, each unit consisting of a pulley mounted overhead and a second pulley equal in size and mounted directly below in a cross-head frame which slides in vertical ways.

The sections of belt to be tested were fastened with plate and split rivet type fasteners. After placing the belt over the pulleys the desired weight was suspended from the cross-head frame, which holds the lower pulley. The upper pulley was driven at the desired speed. The machine was designed to permit the use of a considerable range of pulley sizes, tensions and speeds. All of the pulleys had standard crown faces.

Most of the belt samples were 3 in. wide when tested, but all of the results are reported in unit tension in pounds per ply inch, so that where a difference of width was necessary it would not influence the results. The belts for the tests without power transmission were made up uniformly to a 10-ft. length and the vertical ways would permit a sufficient change of center distances so that various size pulleys could be used with this belt length.

Each test was continued until ply separation took place to the extent of 5 in. of length along the belt. The reason for the 5-in. standard is the difficulty of inspecting the tests often enough to find the exact moment when the first evidence of ply separation occurs. Permitting the ply separation to extend itself to some definite amount, gives opportunity of very definitely determining the end point of the test.

The ply separation in many cases started close to the fastened joints, but in many other cases was found in sections remote from the joint, so that the fastener influence was not large and the presence of the fastener was considered to be a desirable coordination with typical service conditions.

Some of the combinations of the variables mentioned, resulted in tests of such long duration that the whole program consumed a very long period of time, and for this reason it was necessary to confine the testing to two individual belts, each of which was large enough to provide a large number of test specimens.

The belt which is referred to as belt A was a 6-ply belt and was tested as such. The belt referred to as belt B was an 8-ply belt. For the tests of less than 8-ply on belt B one or more of the plies were removed, starting from the pulley side. Thus we obtained comparable

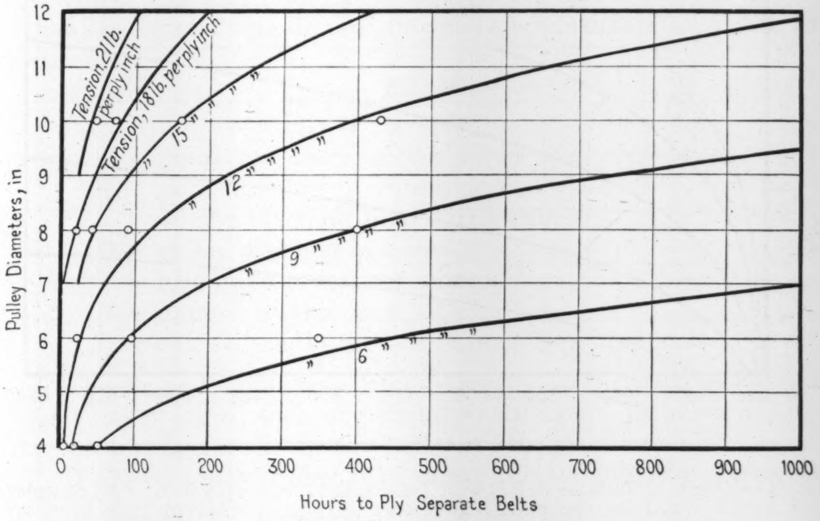

FIG. 1.—Results of Tests on Belt A, 6 Ply, with a Belt Speed of 1500 ft. per minute.

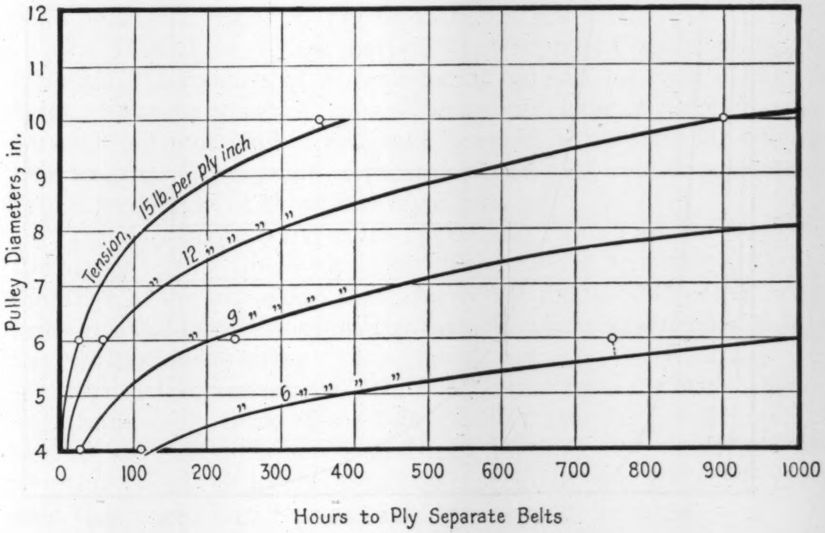

FIG. 2.—Results of Tests on Belt B, 6 Ply, with a Belt Speed of 1500 ft. per minute.

samples of 4, 5, 6, 7 and 8 plies, without introducing a variable in the quality of the belt itself.

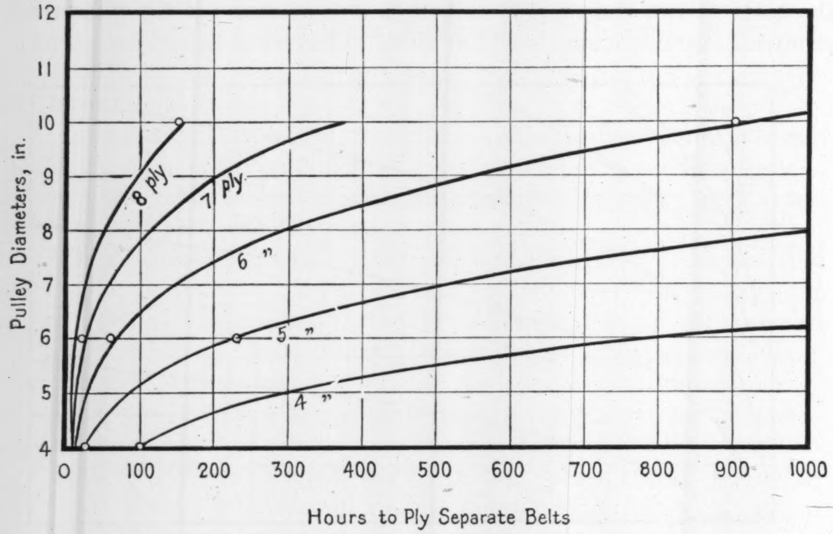

FIG. 3.—Results of Tests on Belt B with Tension of 12 lb. per ply inch on All Samples, Belt Speed of 1500 ft. per minute.

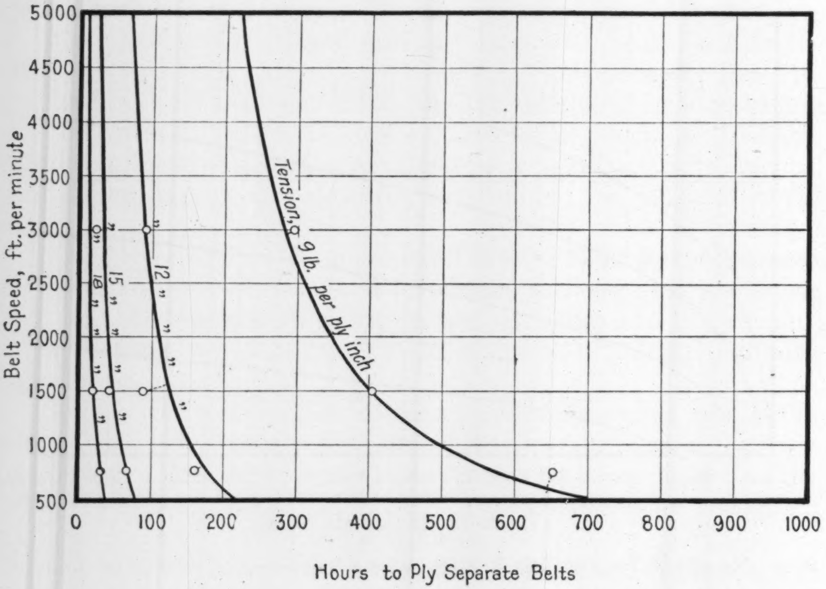

FIG. 4.—Results of Tests on Belt A, 6 Ply, Showing Effect of Belt Speed. All pulleys 8 in. in diameter.

DISCUSSION OF DATA

All of the data were considered as a composite whole and the following formula was devised to closely approximate all of the test data:

$$H = \frac{KD^{5.35}}{V^{0.5}P^{6.27}T^{4.12}}$$

where H = number of hours to obtain 5 in. of ply separation,
K = numerical factor depending on belt quality, belt length and possible other factors not studied in this test,
D = pulley diameter in inches,
V = belt speed in feet per minute,
P = number of plies, and
T = unit tension in the belt in pounds per ply inch.

The above formula was based primarily on that part of the data which was obtained without power transmission. In every instance the belt was operated over two pulleys of the same size.

It will be apparent that the value of this formula does not consist in providing a method to predetermine the length of time that a belt will operate under given conditions, but rather in providing an approximate method of gaging the relative severity of various operating conditions with respect to ply separation of the belt.

In Figs. 1 to 4, the curved lines represent solutions of this formula. The values of K were found by trial for each of the two belts. The constant K, of course, would have a different value for each different kind of belt, and it would be different for different belt lengths. The points represent actual test results, each point being the average of three individual tests.

The data represented in the figures and Table I are only a part of the actual testing which was done on these belts, but they are representative of the whole and show clearly the relationship of the actual testing to the foregoing composite formula which was developed from the results of this testing.

Figure 1 represents the results of actual tests on belt A, which was tested 6-ply thick with a belt speed of 1500 ft. per minute. A number of pulley diameters and unit tensions were used and the resulting hours until ply separation occurred are recorded, along with the curved lines representing the composite formula.

Figure 2 represents the results of tests on belt B, tested as a 6-ply belt with a belt speed of 1500 ft. per minute and with diameters and tensions varying as in the case of Fig. 1.

Figure 3 records the results of test on belt B on one tension only, but with five different thicknesses of belt. As before stated, all of these samples were taken from the same roll of 8-ply belting, with plies removed from the pulley side to obtain the 4 to 7-ply, inclusive, samples. The 6-ply line on Fig. 3 is identical with the 12-lb. tension line in Fig. 2.

Figure 4 shows some tests which were made to determine the effect of belt speed. Belt A was used, 6-ply thick, with 8-in. pulleys. The effect of belt speed is shown with three different velocities and four different tensions.

Two widely different series of tests are given in Table I, which shows comparisons made between a belt carrying useful horsepower and a belt running without horsepower load. In both cases the tensions were closely controlled. These tests were made on the 75-h-p. dynamometer.

TABLE I.—RESULTS OF PLY-SEPARATION TESTS ON BELTING.

Description of Tests	Running Idle[a]	Running Under Load (Dynamometer)[b]	Ratio, Results in Load Tests to Running Idle Tests
Two 18-in. pulleys 1700 ft. per minute, 24-ft. belt length	3794 hours	1400 hours	
	2393 "	1156 "	
	2520 "	1300 "	
	1746 "	1176 "	
	3196 "	1220 "	
Average	2724 hours	1250 hours	46.0 per cent
Above tests converted to 1500 ft. per minute and 18-ft. length ... Average	2170 hours	1000 hours	46.0 per cent
Two 10-in. pulleys 1500 ft. per minute, 18-ft. belt length	110 hours	48 hours	
	110 "	43 "	
	102 "	40 "	
	100 "	48 "	
Average	105.5 hours	44.8 hours	42.5 per cent
10-in. tests in percentage of converted 18-in. tests	4.9 per cent	4.5 per cent	

[a] Tight-side tension, 22.5 lb. per ply inch; slack-side tension, 22.5 lb. per ply inch.
[b] Tight-side tension, 30.0 lb. per ply inch; slack-side tension, 15.0 lb. per ply inch.

It will be noted that the number of hours was reduced by changing from 18-in. to 10-in. pulleys by approximately the same percentage, whether the belt is carrying a load or running idle under tension. The two series were made with different lengths, but assuming that the length is a first power function and making a correction for the slight difference in speed, it will be seen that when the belt was running idle, the hours were reduced to 4.9 per cent and when carrying load the hours were reduced to 4.5 per cent. The amount indicated by the formula is 4.3 per cent which shows the close relationship of the tests to the formula.

The effect of adding load to the belt was practically the same in both series of tests. Changing from a tight-side and slack-side tension of 22.5 lb. per ply inch to a load condition where the tight-side tension is 30 lb. and the slack-side tension is 15 lb. per ply inch, the number of hours was reduced to 42.5 per cent in the case of 10-in. pulleys and 46 per cent in the case of 18-in. pulleys. The first percentage would be accounted for by the formula if the tension while running idle was increased from 22.5 to 27.5 lb. The second percentage would be accounted for by the formula if the tension while running idle was increased from 22.5 to 27.2 lb.

This work indicates that the effect of adding load to a belt is merely an adjustment of tension and does not change the relationship in the formula which was made up from the tests without horsepower load. For practical use of the formula it may be considered that the relative effect of the tensions in two drives is determined by using the tight-side tension in the formula.

It will be observed from the figures that the lines drawn in accordance with the formula fit the actual tests closely. This establishes the fact that each of the variables influences ply separation of a rubber belt very closely to the extent indicated by the exponents in the formula.

CONCLUSIONS

While not all variables in belt driving were studied, and while the tests were necessarily confined to two lots of belting, due to the extremely long time required to get results, the following conclusions appear to be fully justified by these tests.

1. Unit tension, number of plies and pulley diameters influence ply separation as relatively high power factors.

2. Belt speed influences ply separation, but to a lesser degree than the factors given above, except of course, that with high speeds, the belt speed causes centrifugal tensions of considerable magnitude in the belt.

3. When several of these factors are present in adverse relationship within the same belt drive, a very large reduction of belt service may result.

4. With a given total tension necessary in a belt, the length of time that ply separation can be avoided is longer with thin belts than with thick belts. The limiting factor in applying this knowledge is the fact that if the number of plies used is too small, the resulting stretch may be objectionable.

5. While the manufacturer of rubber belt may improve the resistance of the belt to ply separation by several times, as has been accomplished in recent years, the user of the belting has it within his power to increase or decrease the severity of the belt installation by much larger amounts by his selection of pulley sizes, tensions, number of plies and belt speeds.

DISCUSSION

Mr. V. A. Cosler[1] (*presented in written form*).—Referring to the paper by Mr. Kimmich, it seems to me the results can more properly be considered as those obtained on a belt or belts with a given type fastener. In the discussion under test methods it was indicated some of the separation took place near the fastener. Our experience in testing belts has indicated that the type of fastener has probably more influence on ply separation than on any other characteristic cause of failure. I think that a repetition of this same line of testing using vulcanized splices might add valuable information, and probably even warrant a change in the formula given to represent causes of ply separation. I appreciate that the formula is intended to represent a rather narrow construction of possible causes of ply separation and that in turn the ply separation is today a comparatively minor cause for belt failure. However, even this narrowly restricted formula should carry the warning that methods of fastening can further restrict its use.

We have calculated the K value from the figures in Table I of the paper. The first test figures give results of tests run under the following conditions: 18-in. pulley, 1800 ft. per minute, 24-ft. belt length, $H = 2724$ hours.

Correcting H to 18 ft. length, $H = 2724 \times \frac{18}{24} = 2045$ hours.

Substituting, we find the value of K to be of $5820 \times P^{6.27}$

The results show the second set of tests under the following conditions: 10-in. pulley, 1500 ft. per minute, 18-ft. belt length, $H =$ 105.5 hours.

Substituting the values in the formula for K, $K = 6620 \times P^{6.27}$. This shows a variation in the K factor of about 14 per cent.

Granted that the belts tested were of the same quality, it would seem that there is a possibility that the difference in K value obtained, would represent an important variable in the test itself. This viewpoint has some color in view of the fact that the number of hours running idle for the first test has a variation within the set of tests somewhat in excess of this percentage, since one result indicates 1846 hours and the other one 3794 hours run under the same conditions.

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[1] Technical Superintendent, Mechanical Division, The B. F. Goodrich Co., Akron, Ohio.

LABORATORY FLEXING TESTS AS AN AID IN INVESTIGATING THE PNEUMATIC TIRE CARCASS

BY H. A. DEPEW[1] AND H. C. JONES[2]

SYNOPSIS

In an investigation of laboratory methods that may be applied to the development of the pneumatic tire carcass, it has been found that a pulley flexing test using small belts gives information that should be applicable to high-pressure tires. A free bend test gives additional information when very low air pressures are used, and a jerking test gives information regarding the quality of the cord.

The tests indicate that tire carcass construction should be considered in connection with the compounding of the pneumatic tire carcass.

Tire tests, both service and test wheel methods, are generally used for carcass development, supplemented to a limited extent by laboratory tests, which include stress-strain tests on the compound and the cord, friction tests to measure the force necessary to pull the rubber compound from the cord, and pulley flexing tests. Owing to the cost and difficulty of reproduction of tire tests, it is desirable to use laboratory tests in so far as possible, although it will be impractical to eliminate tire tests as final checks before putting laboratory information into production and as a general method of attack for special problems in design. Among the important problems that lend themselves especially well to laboratory methods are: (1) Insulation of tire cord, including thickness of skim and spacing of the cord; and (2) rubber compounds (both before and after aging), including composition and state of cure.

In choosing laboratory methods, it was decided to use flexing methods, with tension tests on the compound as an aid in judging state of cure. Friction tests were not made since they would be meaningless for indicating the bond between rubber and cotton when the cords are well separated in rubber.

The test pieces chosen were six-ply cord belts 9 in. long and 1 in. wide, with three layers of cord running lengthwise and three alternate layers crosswise. These belts were assembled and vulcanized according to the methods described by Gibbons.[1] Belts are not tested until after five days' storage since the flexing life is relatively short immediately after vulcanization and it increases for from one to five days before becoming constant, depending on the compound.

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[1] Chief, Rubber Section, Research Division, The New Jersey Zinc Co., Palmerton, Pa.

[2] Research Chemist, Research Division, The New Jersey Zinc Co., Palmerton, Pa.

A ply thickness of 0.050 in. in a six-ply belt 9 in. long and 1 in. wide corresponds to a volume of rubber compound of 2.01 cu. in. when 17 cords per inch are used, and to a volume of rubber compound of 1.68 cu. in. when 25 cords per inch are used. The additional volume of rubber for thicker plies can be calculated directly from the area and the additional thickness.

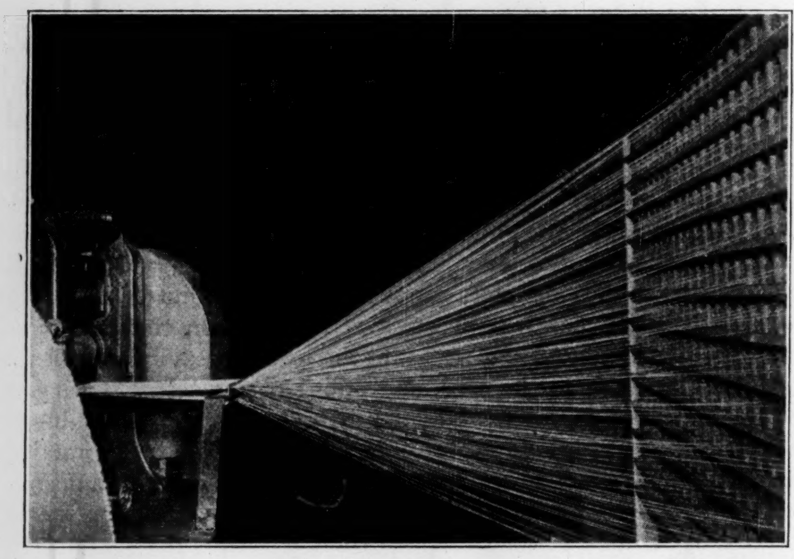

FIG. 1.—Rubber Impregnated Cord Feeding from Small Bobbins Through Combs to the Calender Where They Become Embedded in a Sheet of Rubber.

The details of coating the cord with a rubber compound are briefly described with the belief that they will be helpful. The tire cord, received on large bobbins, is dried and passed through a rubber cement, consisting of the compound dissolved in benzene. After drying, the cord is rewound on small bobbins and fed through two combs to a three-roll calender and skimmed on one side (Fig. 1). The compound used in skimming is the same as that used in making the cement. The rubber sheet with the cords firmly in place is again passed through the calender and skimmed on the other side to the desired gage. When the stock cools, it is cut into squares, plied up, and cured according to the method of Gibbons.[1]

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[1] *Industrial and Engineering Chemistry* (Analytical Edition), Vol. 2, No. 1, p. 99 (1930).

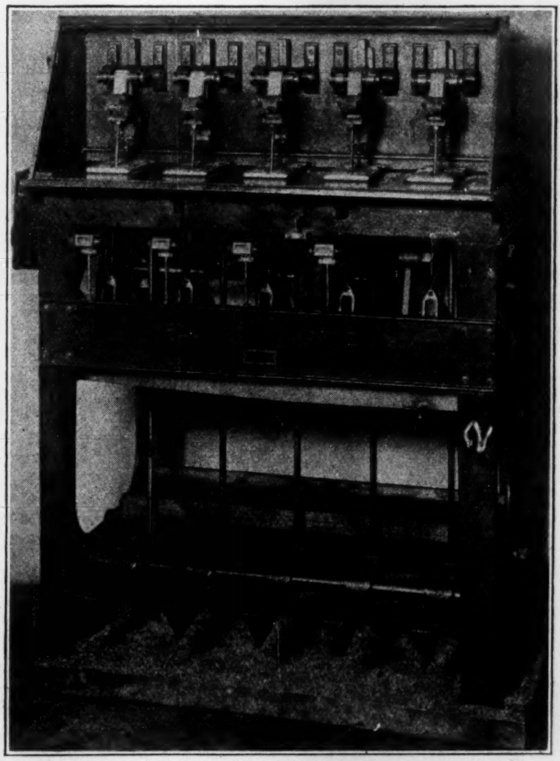

FIG. 2.—Pulley Flexing Machine.

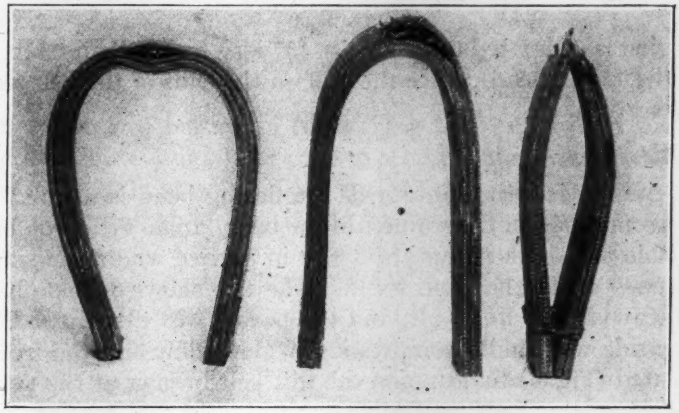

FIG. 3.—Typical Pulley Flexing Failures.

If a 100-lb. (45.5 kg.) load had been applied rather than the 150-lb. (68.2 kg.) load, and only belts with 25 ends had been used, all the failures would have been due to separation.

METHODS OF FLEXING

The belts are tested on three types of flexing machines: (1) pulley test (constrained bending); (2) free bend test; and (3) jerking test. The pulley test is well-known and the other two are experimental tests.

Pulley Test:

The United States Rubber Co. flexing machine built for the Society's Committee D-11 on Rubber Products by the Henry L. Scott Co. is used for the pulley test (Figs. 2 and 3). In this test, the small belt is made to conform to a $\frac{9}{16}$ in. pulley and repeatedly flexed (175 cycles per minute) under a specified load of 150 lb. (68.2 kg.). The belt tension is computed to be 81½ lb. (37 kg.) rather than 75 lb. (one-half of the 150-lb. load), since the pull on the ends of the belt was not exactly vertical.

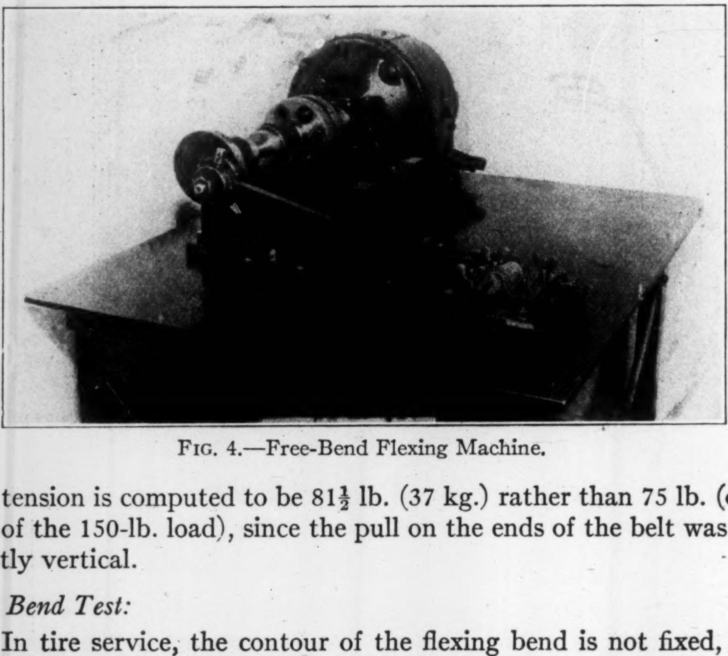

FIG. 4.—Free-Bend Flexing Machine.

Free Bend Test:

In tire service, the contour of the flexing bend is not fixed, but depends somewhat on the stiffness of the belt. In an article on balloon tires,[1] Hale showed a picture of a tire in service where the side wall had actually folded back on itself. The tire shown was probably a 21/7.30 carrying 20 lb. of air, and the flexing was extreme. Folding puts the side wall under compression at one point and the free bend is simulated (Fig. 4) by gripping the test belt in jaws at the two ends and moving them back and forth with a reciprocal motion at high speed (1150 cycles per minute).

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[1] *Journal*, Soc. Automotive Engrs., Vol. 13, No. 1, p. 41 (1923).

Jerking Test:

In addition to tire failures from separation, there are failures due to cord breaks and the ability of the cotton to withstand repeated stress is of considerable importance. With this in view, a jerking test was introduced (Fig. 5) that is intended to simulate the loading strains induced in a tire carcass in service. A dead weight applies a load which corresponds to the cord tension produced by the air pressure within the tire. Road blows, which are superimposed in service, are comparable to the force applied by the crank arm through the coil spring. The cord tension in the jerking test varies from a constant load of 0.89 lb. (0.40 kg.) per cord to a maximum intermittent load of 5.48 lb. (2.49 kg.) per cord. Belts with 17 cord ends per inch are under a constant tension of 45.2 lb. (20.55 kg.) and a maximum intermittent load of 280 lb. (127.4 kg.). The belt tension using 25 ends per inch is 66.4 lb. (30.2 kg.) constant load and 413 lb. (188 kg.) maximum intermittent load. In the jerking test, the belt is not supported vertically due to the development of failures in the jaws.

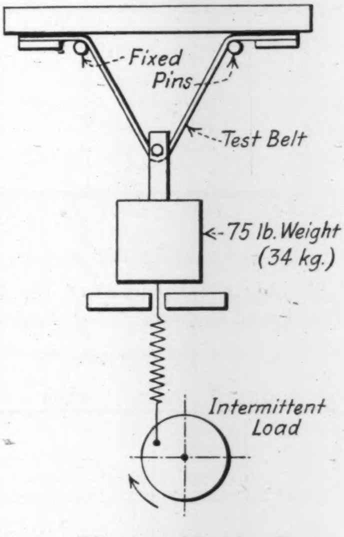

FIG. 5.—Diagram of Jerking Test.

RESULTS AND DISCUSSIONS

Table I gives data showing the range of reproducibility of the results of the three tests.

Table II (summary of detailed data given in Figs. 6, 7, and 8) shows that an increase in ply thickness and a decrease in the number of ends within the limits investigated increases the pulley flexing life; or in other words, it might be stated that with more rubber between

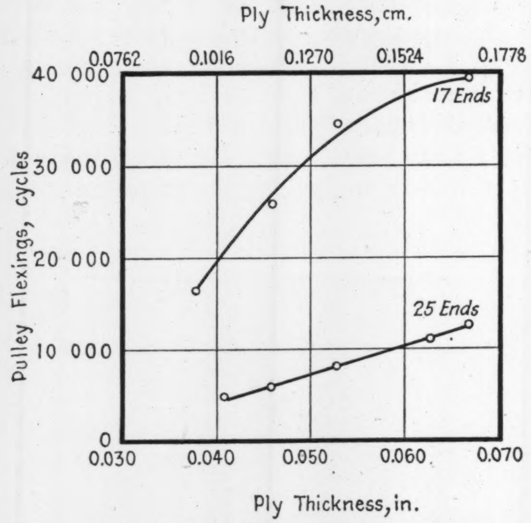

FIG. 6.—Showing the Influence of Ply Thickness and Number of Ends on Pulley Flexing Life.

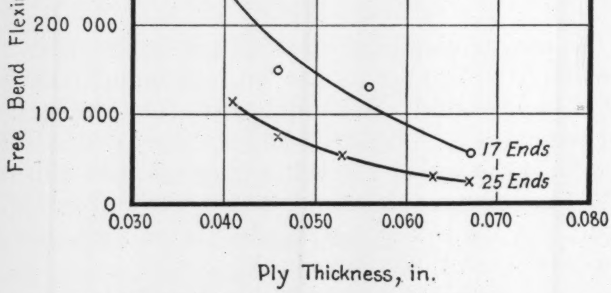

FIG. 7.—Showing the Influence of Ply Thickness and Number of Ends on Free Bend Flexing.

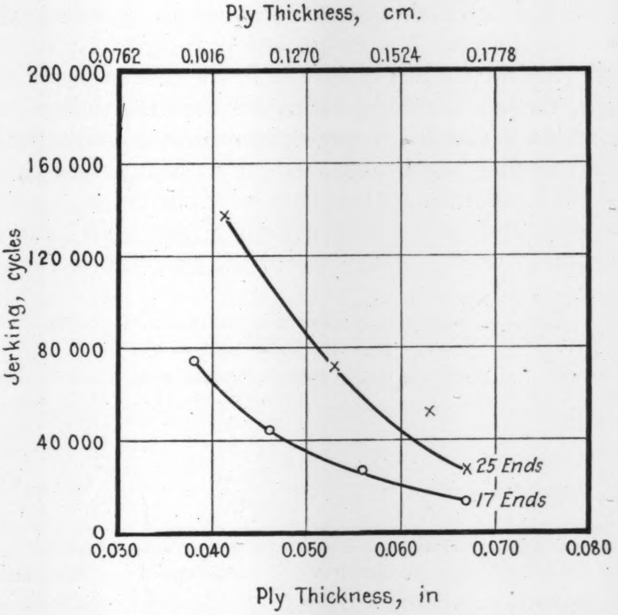

FIG. 8.—Showing the Influence of Ply Thickness and Number of Ends on the Ability to Withstand Repeated Jerking.

The tests were made with the same tension per unit cord and not with the same tension on the belt.

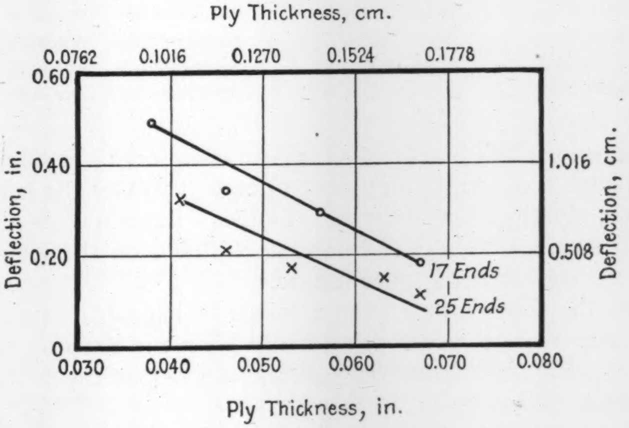

FIG. 9.—Showing the Influence of Ply Thickness and Number of Ends on the Stiffness of the Belt.

The test was made by resting the 1-in. (2.54-cm.) wide belt over two supports 6 in. (15.25 cm.) apart and placing a load of 0.44 lb. (0.2 kg.) at the center and measuring the deflection at that point.

the cords (better insulation from one cord to another), the pulley flexing life is increased. Better insulation of cords is generally recognized to give longer tire life, especially in the case of heavy-duty tires. Accordingly, there is a strong indication that the pulley flexing test is a guide to the flexing life of present-day tires as stated by Gibbons, and it is an especially applicable method for heavy-duty tires.

It has been pointed out that when very low air pressures are used, the tire section tends to flex with more of a free bend; accordingly, in any development work looking toward the adoption of extremely low air pressures, the free bend test should be considered. Table II shows that although a decrease in number of ends increases the belt life, an increase in ply thickness decreases the life. Examination of the belt during flexing indicates that compressive forces on the inside of the bend of the thicker belts cause failure.

TABLE I.—SHOWING REPRODUCIBILITY OF RESULTS.

TESTS ON BELTS CUT FROM THE SAME PAD

TEST	PULLEY FLEXING TEST, CYCLES	FREE BEND TEST, CYCLES	JERKING TEST, CYCLES
No. 1	30 600	57 100	62 100
No. 2	33 100	51 700	65 500
No. 3	31 000	54 600	63 200
No. 4	33 900		

REPEAT PULLEY FLEXING TESTS MIXING NEW BATCHES OF THREE DIFFERNT COMPOUNDS.[a]

	COMPOUND A	COMPOUND B	COMPOUND C
Original Test	37 400 cycles	38 500 cycles	25 200 cycles
Repeat Test	37 600 "	43 900 "	27 700 "

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[a] Each value is the average of four pulley flexing tests.

TABLE II.—EFFECT OF INCREASED INSULATION OF CORDS ON BELT LIFE.

	INCREASE IN PLY THICKNESS	DECREASE IN NUMBER OF ENDS
Pulley Test	increases life	increases life
Free Bend Test	decreases life	increases life
Jerking Test	decreases life	decreases life

From the above information it would be logical to expect a thick side wall super-tire to break down badly when run flat since free-bend flexing is approximated, and the authors believe that this is the general experience of motorists.

The value of the jerking test for determining the kind and amount of cotton is shown by determining the comparative jerking life of a 25-cord-end belt with that of a 17-cord-end belt under a jerking tension ranging from 45.3 lb. minimum to 280 lb. maximum. The 25-end belt lasted for 11,385,000 cycles whereas the 17-end belt withstood only 13,000 cycles.

In order to investigate the effect of the amount of insulation of the cords when different numbers of cord ends are used, the total belt tension is adjusted as described earlier so that the average individual cord tensions are equal. The tests (Fig. 8) show that the best jerking life is obtained when the cords are poorly insulated; that is, with a maximum number of ends and a minimum ply thickness. It is apparently desirable to reduce the movement of the individual cords relative to one another to a minimum.

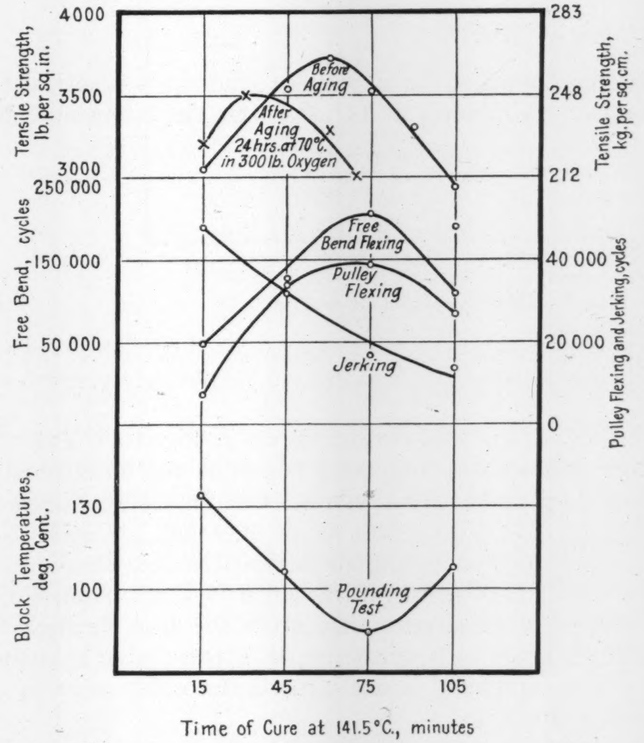

FIG. 10.—Showing the Influence of Cure.

Seventeen-end belts with a ply thickness of. 0053 in. (0.135 cm.).

It should be kept in mind that continual flexing weakens the cords and that a tire with low cotton strength might have sufficient strength for all emergencies if the cords were not weakened due to poor flexing qualities.

The behavior of the test belts in the three tests is influenced to a considerable extent by the stiffness of the belt. The stiffness is determined by the amount and kind of rubber compound. For completeness, the effect of ply thickness and number of ends on stiffness is shown in Fig. 9.

Effect of State of Cure:

The tests shown so far have been made at a practical technical cure; namely, 45 minutes at 141.5° C. for the following compound:

Smoked Sheet	460 g.
Pale Crepe	460 g.
Sulfur	37 g.
Mineral Rubber	45 g.
Stearic Acid	4.5 g.
Medium Pine Tar Oil	18.0 g.
Age-rite Resin	18.0 g.
D. O. T. G	9.0 g.
Red Label Kadox	280.0 g.

The effect of state of cure is shown in Fig. 10. The maximum tensile strength for the compound comes at the 60-minute cure for the unaged stock and at the 30-minute cure for the aged stock. Superior flexing by the belts comes at an over-cure (75 minute). Test blocks of the compound subjected to repeated pounding[1] heat up and reach an equilibrium temperature which is a minimum for the 75-minute cure—the same cure that gives the best flexing. Since a resilient stock heats to a minimum, it is reasonable to assume that resiliency in a compound is one important consideration in choosing a tire carcass compound.

The apparently anomalous results of increased jerking life with decreased cure are possibly due, in part, to flow of the plastic undercured rubber compound allowing better equalization of tension among the cords.

The influence of aging on the pulley flexing life is shown in Fig. 11. Over the range of cures, there is an appreciable reduction in flexing life.

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[1] H. A. Depew and E. G. Synder, "The Use of a Group of Performance Tests for Evaluating Rubber Compounds that must Withstand Repeated Compression," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 962 (1929).

Effect of the Composition of the Compound:

The flexing method of investigation has been applied to the problem of choosing rubber compounds for the pneumatic tire carcass. Two compounds that tested about 100 per cent apart in the pulley test when using a belt built with 17 ends and a thick ply were approximately equal when 25 ends and a thin skim were used. Good insulation of the cords accentuates differences in ply separation, and therefore good insulation is the preferred condition when testing compounds for ply separation. This influence of belt construction on flexing life with different compounds emphasizes the importance of studying tire construction in connection with the compounding of the pneumatic tire carcass.

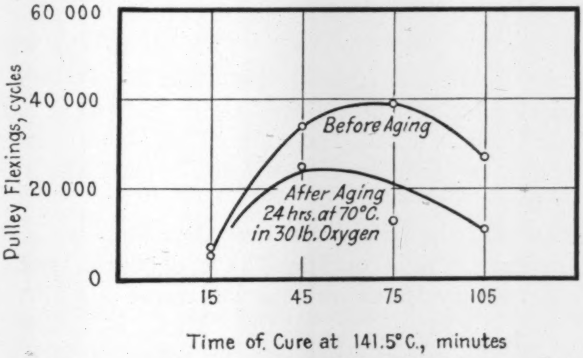

FIG. 11.—Showing the Influence of Aging on Pulley Flexing Over a Range of Cures.
Seventeen-end belts with a ply thickness of 0.053 in. (0.135 cm.).

DISCUSSION

MR. A. W. CARPENTER[1] (*presented in written form*).—The authors are to be complimented on their very interesting paper. The details concerning the preparation of the test specimens are well given and the importance of care and precision in this phase of flexing investigations can hardly be overestimated. The use of the experimental calender, set up to handle coating operations on weftless cord is of more than passing interest as applied here in test work. In referring to the test specimen as a belt, the authors risk being somewhat misleading, although the strip specimen is really used like a belt in the pulley flexing test.

It is noted that the pulley test described employs $\frac{9}{16}$-in. pulleys and 150-lb. loading. These conditions have, of course, been frequently used. Our laboratory, however, has had more satisfactory results using $1\frac{1}{4}$-in. pulleys and 100-lb. loading. These less severe conditions do not accelerate the test as much, but we believe a better end point due to ply separation alone is secured. Under the latter conditions broken failures as shown in Fig. 3 of the paper are practically never obtained.

The two new tests described will undoubtedly prove of great value. The free-bend test appears to be quite suitable for arriving at evaluation of general characteristics. The jerking test, however, would seem to be subject to rather more question. It would be interesting to know the speed used for the test, since at high speeds much heat might develop which could cause failure even by charring the cords. This test would seem to favor undercure of samples, as under such conditions there would be better opportunity for flow and distribution of the load.

The authors point out that the results (Fig. 8) show that the best jerking life is obtained when the cords are poorly insulated. Although this appears to be indicated, if that conclusion holds strictly, what would be true in the case of minimum insulation or, as an extreme, none at all? Such a theoretical tire should have best life. Actually, of course, it would be of no value. From tests on fabrics made in our physical research laboratories, we believe that the longer life of 25-end fabric belts is to be explained by a better distribution of stresses among the individual cords and probably a decreased stress in the cords of the 25-end samples.

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[1] The B. F. Goodrich Co., Akron, Ohio.

MR. F. D. ABBOTT.[1]—I have one or two questions I should like to ask relative to the work which the authors conducted. My questions are prompted solely by the fact that the Research Laboratory of the Firestone Tire and Rubber Co. has one of the Scott flexing machines and to date has reported—in attempts made from time to time—failure to get results as satisfactory as those which the authors report. Furthermore, Subcommittee XVI of the Society's Committee D-11 on Rubber Products has reported unsatisfactory results. I am wondering, in view of this fact and in view of their own good results, if the authors can suggest how the committee could get better results in tests on belting or other laboratories on tire carcass sections.

I should like also to know why the cord was dipped in cement before skimming. In other words, is gum dipping necessary or essential for proper insulation of the cords during a flexing or service test?

Other questions are: How well are the cords in a tire spaced as compared to spacing in the pads? Is it not necessary to use a single definite type of fabric or cord construction ("creel") to secure satisfactory results, and what physical characteristic of the rubber is it which causes this ply separation?

MR. C. H. ZIEME.[2]—I would like to ask whether the results obtained on the flexing machine with a test piece composed of cords laid lengthwise and crosswise to the direction of pull are comparable with flexing results obtained on a tire carcass in which the cords are alternately laid on the bias.

MR. H. A. DEPEW.[3]—Mr. Carpenter mentions the desirability of using the 100-lb. load instead of the 150-lb. load. The 100-lb. load does produce pure separation to a greater extent than the 150-lb. load, but a tire fails partly by simple flexing and partly through the load, and our tests indicated that the 150-lb. load would more nearly duplicate tire conditions. Furthermore, the tests are more reproducible and rapid with the 150-lb. load.

The jerking test was run at a rate of 3 cycles per second. This speed was not great enough to cause the belt to heat up more than 15 to 20° C.

As for the statement that our tests indicate that undercures would be better, we believe that so far as jerking goes, they would be decidedly better, and that a tire with practically no insulation or a minimum insulation in the lower plies would show fewer fabric breaks than a tire with more insulation. If carried too far, however, the tire would fail through separation, as indicated by the pulley test.

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[1] Research Physicist; Manager of Physical Testing Division, Firestone Tire and Rubber Co., Akron, Ohio.

[2] Technical Superintendent, The Republic Rubber Co., Youngstown, Ohio.

[3] Chief, Rubber Section, Research Division, The New Jersey Zinc Co., Palmerton, Pa.

In this connection we would like to point out that if a person were to build a tire ideally, he would start at the band ply using fairly low insulations, that is, ply thickness; he would use a relatively low state of cure, he might put in some softener such as M.R. that would make a dead stock and then when he got into the upper two to four plies, next to the cushion he would tighten the cure by the use of more accelerator to the point where he would have a very snappy stock and he would reduce the number of cord ends from 25 or 26 down to 17 or 18. Then above the carcass the cushion would be cured up tight and it would contain a couple of layers of cord with about 12 or 13 ends per inch, and above this the regular tie strip and an extra heavy tread. A relatively high zinc oxide stock would be used throughout. In the lower plies it would increase jerking resistance and in the upper plies it would improve flexing.

Now referring to the questions that Mr. Abbott brought up: Mr. Gibbons checked laboratory belts as well as we did; the committee was using belts that were made of square-woven fabric, whereas Mr. Gibbons and we were using cord. I believe that the uneven results with square-woven fabric obtained by the Subcommittee on Belting has been due to the small size of the test belt. There is considerable variability in belts and to make this test applicable to belts, it is necessary to use larger testing machines. The dynamometer test, which is considered reliable, tests an entire belt.

In regard to the question as to why we dip the cord in cement, this was a matter of convenience with us. If we dip the cord in cement, we keep it in position in the rubber sheet as it came off the calender much better than we could by frictioning on a small calender.

As to how well the cords are spaced, we believe that after a comparison of these belts with tires you will agree that they are spaced very well; after all, they represent hand work and ought to be good.

Referring to the cause of separation, we have pointed out that a resilient stock does not separate easily. We believe that if a stock has a high permanent set, the spacing of the cords becomes distorted and under flexing it has to separate somewhere.

Mr. Zieme asked regarding placing the cords on a bias rather than at right angles. I think there is no question that placing cords on a bias in our test would give different results than if we had placed the cords at right angles. However, I believe that the results would be comparable. We have been investigating compounds, cure, ply thickness, and the number of cord ends, and the effect of different bias angles would simply be to bring all the results to a different level.

MOTOR PERFORMANCE AS DETERMINED BY FUEL VOLATILITY

By George Granger Brown[1]

Synopsis

The ease with which a motor will start, the length of time required to warm it up, and the character of its general performance are almost wholly dependent upon the volatility of the fuel as indicated by the A.S.T.M. distillation curve.[2] The 10-per-cent point is related to the lowest engine temperature at which satisfactory starting may be obtained, and the lowest mixture temperature at which the car may be operated. The 35-per-cent point is related to the lowest mixture temperature at which satisfactory performance may be obtained during the warming-up period and therefore determines the length of time necessary to warm up the motor. The 65-per-cent point is related to the lowest mixture temperature at which perfect performance can be obtained. For these reasons the 10, 35 and 65-per-cent points should be low to insure satisfactory starting, warming up, and general performance. The 90-per-cent point, however, should not be so low as to indicate a dry mixture, for this means loss in power or acceleration with many modern cars equipped with heated manifolds and accelerating devices. The vapor pressure of the fuel should not be so high or the 10-per-cent point should not be so low as to indicate trouble from vapor-lock.

The relations presented in this paper make it possible to determine the volatility characteristic of a fuel for any desired engine performance.

The universal method of estimating the volatility of fuels is the A.S.T.M. distillation method.[2] The importance of the first 10 to 20 per cent in indicating the ease of starting is now generally recognized, but the relative importance of the middle and upper parts of the distillation curve has not been demonstrated. In this paper the distillation curve is always plotted with the loss added at the lower end because this method gives a more accurate picture of the volatility of the fuel, which can be interpreted directly into terms of engine performance.

Equilibrium Volatility

Although generally used as a relative term, "volatility" designates such an important characteristic as to demand a quantitative defini-

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[1] Professor of Chemical Engineering, University of Michigan, Ann Arbor, Mich.

[2] Standard Method of Test for Distillation of Gasoline, Naphtha, Kerosine and Similar Petroleum Products (D 86 - 27), and Standard Method of Test for Distillation of Natural Gas Gasoline (D 216 - 27), 1927 Book of A.S.T.M. Standards, Part II, pp. 378 and 387, respectively.

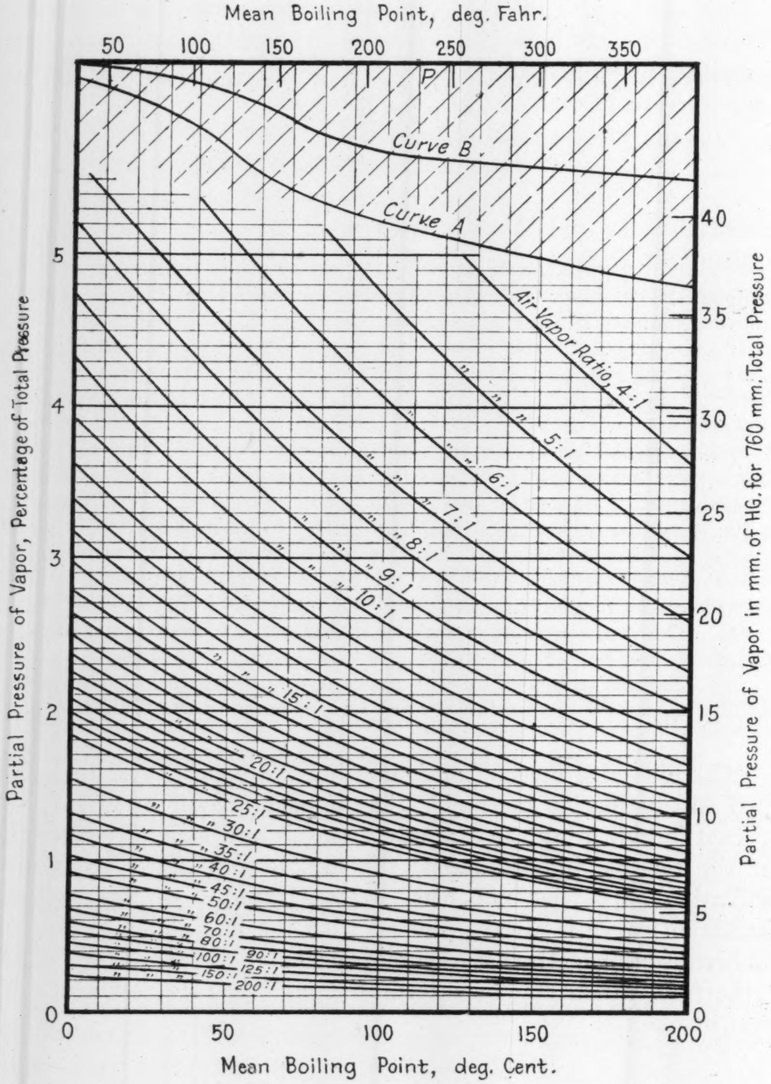

FIG. 1.—Chart for Estimating Partial Pressures of Fuel Vapors.

tion. In order that the term may indicate a characteristic of fuel independent of the dimensions of the apparatus, in this paper the volatility of a fuel is regarded as the percentage by weight vaporized under equilibrium conditions at specified temperature, pressure and air-fuel ratio. A careful study of equilibrium volatility[1] indicates that this property can be best determined by means of the continuous equilibrium vaporization or "flash vaporization" curve. In order to make this calculation the molecular weight of the vaporized portion of the fuel and the vapor pressure of the residue must be known. However, this information is not available from the ordinary equilibrium vaporization, and the molecular weight of the vapor must be estimated from some known property of the vapor, such as its mean boiling point.

Assuming that the molecular weight of the vapor formed when a specified percentage by weight of the fuel is vaporized under a low partial pressure, as in the air distillation, is the same as when the same percentage by weight is vaporized in the absence of air, as in the continuous equilibrium vaporization, the partial pressure of fuel vapor in any resultant air-vapor mixture may be estimated as a function of the average boiling point of the vaporized portion. This has been done, as indicated in Fig. 1, for paraffins, average commercial, and highly aromatic gasolines corresponding to curves *P*, *B*, and *A*.

A second assumption, that the vapor-pressure – temperature relationship of the residue from the continuous equilibrium vaporization process is similar to that of a pure hydrocarbon having the same normal boiling point, allows the temperature of the equilibrium air distillation corresponding to any total pressure, resultant air-vapor mixture, and percentage vaporization to be computed readily from the continuous equilibrium vaporization curve, a vapor-pressure chart for the hydrocarbons, and proper use of the chart, Fig. 1. The normal boiling point is the temperature at which the vapor pressure is atmospheric.

James recommended this method for determining the dew points of air-vapor mixtures using the temperature – molecular weight relationship for the olefin hydrocarbons, and the temperature at which 50 per cent by weight was vaporized in the continuous equilibrium vaporization as the average boiling point of the vaporized fuel. If the average boiling point is taken, not as the temperature at which 50 per cent is vaporized, but as the arithmetic mean between the initial and final boiling points on the continuous equilibrium vaporization curve, and the boiling point - molecular weight relationship is corrected for compounds other than paraffins and olefins, satisfactory results may be obtained. In estimating the temperature corresponding to partial volatility, the average boiling point of the vaporized part of the fuel should be taken as the arithmetic mean of the initial boiling point of the entire fuel and the temperature at which the corresponding percentage by weight is vaporized in the continuous equilibrium vaporization.

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[1] G. G. Brown and Skinner, *Industrial and Engineering Chemistry*, Vol. 22, March, 1930, p. 278.

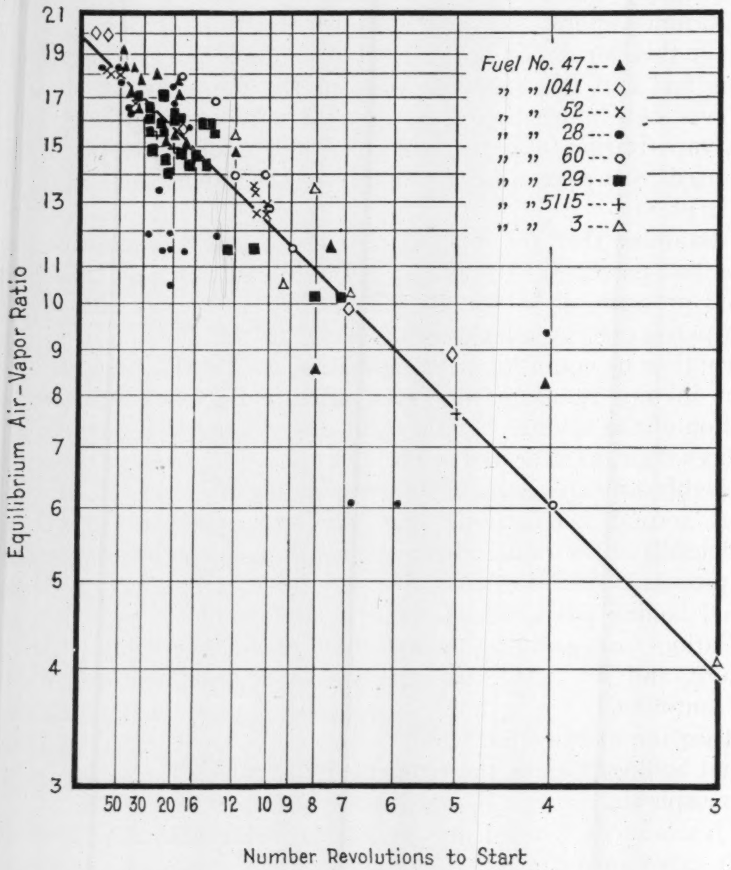

FIG. 2.—Showing Relation Between the Equilibrium Air-Vapor Ratio and the Number of Revolutions Required to Start.

Although the two assumptions on which this method is based are not strictly true, actual deviations do not generally exceed the experimental error in determining the continuous equilibrium vaporization curve (about ±2° C. or 3.5° F.). The molecular weight of the vaporized material is less at lower pressures than would be indicated by the continuous equilibrium vaporization at atmospheric pressure. This is partially compensated in the recommended procedure by using curves representing normal paraffin hydrocarbons as the basis for calculations applied to natural gasoline which contains large amounts of isomeric paraffins, as the normal paraffins have a lower molecular weight than the isomeric paraffins for the same boiling point. A similar compensation is made by the use of curves *A* and *B* as incorporated in Fig. 1, and also by the method of estimating "mean boiling points."

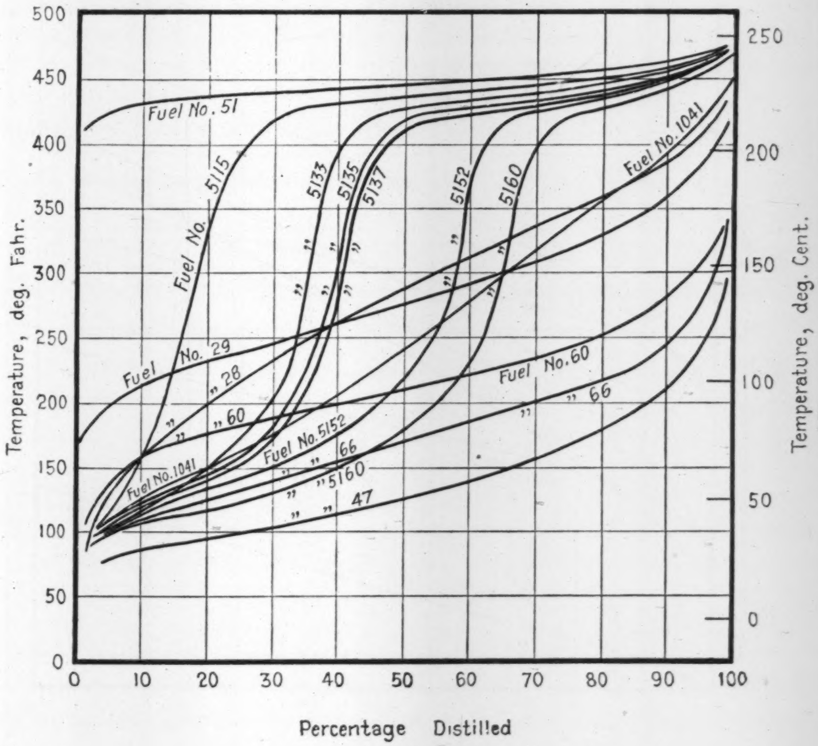

FIG. 3.—A.S.T.M. Distillation Test of Fuels Used.

By use of this mean boiling point and the proper curve, curve *P*, *B* or *A*, the partial pressure of the fuel vapor for any resultant air-vapor mixture may be estimated by Fig. 1. The temperature at which the residue exerts this vapor pressure may then be estimated from a vapor pressure chart and the initial boiling point of the residue.

STARTING VOLATILITY

The most important characteristic of a fuel is its ability to start the motor in which it is to be used. Previous work based on data obtained with a motor cranked by a dynamometer and equipped with a special fuel jet[1] instead of a conventional carburetor, indicated the relation shown by the straight line in Fig. 2, between the equilibrium volatility of the fuel and the number of engine revolutions required to start. The points plotted in Fig. 2 are the data obtained in the present investigation of the ease of starting a cold motor, when

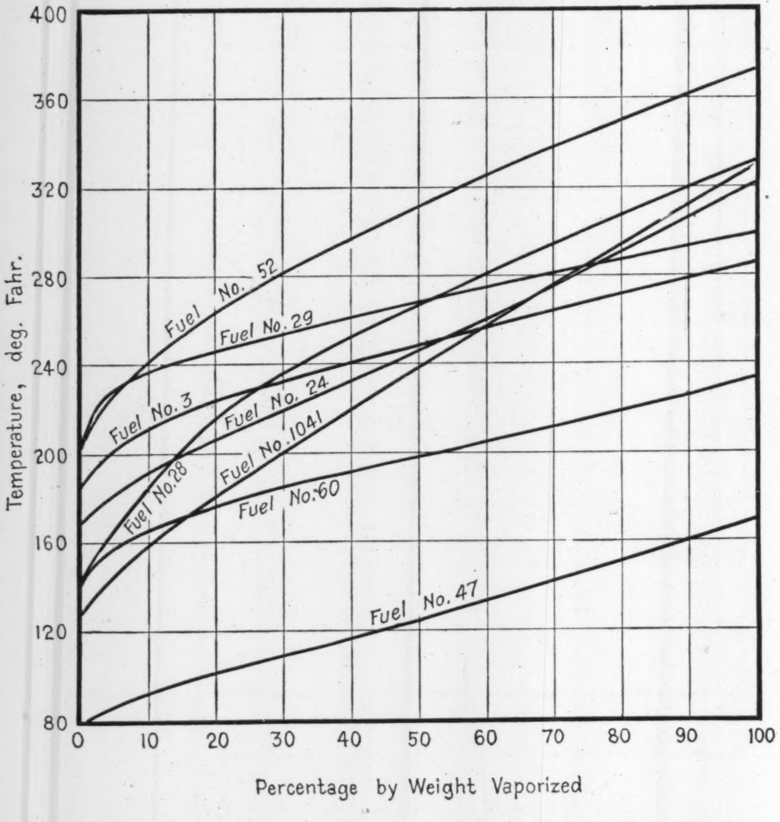

FIG. 4.—Equilibrium Vaporization Curves of Some of the Fuels Used.

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[1] Cragoe and Eisinger, *Transactions*, Soc. Automotive Engrs., Vol. 22, Part I, p. 1 (1927).

cranked by the electric starter supplied from the same battery as was used for ignition, and when equipped with the standard carburetor. These data points fall as close to the straight line as do the original data of Cragoe and Eisinger.

The distillation characteristics of the fuels used are shown in Figs. 3 and 4. The motor was placed in a cold room and tests were conducted over the temperature range from −40 to +80° F. with cranking speeds varying from less than 20 to over 200 r.p.m. As has been frequently observed, starting was found to be far more difficult at low cranking speeds such as 20 r.p.m. than at the higher speeds such as 140 r.p.m. However, when the air-fuel ratio supplied by the carburetor was computed for these different conditions, it was found that the same number of engine revolutions were required for a given air-fuel ratio at the carburetor regardless of cranking speed.

TABLE I.—RELATION BETWEEN ENGINE AND A.S.T.M. TEMPERATURES FOR A 1 TO 1 AIR-FUEL RATIO.

Percentage Vaporized	Resultant Air-Vapor Ratio	Engine Revolutions to Start	Ratio, A.S.T.M. Distillation to Equilibrium Air Distillation Temperature	Corresponding A.S.T.M. Distillation Temperatures for Given Engine Temperatures, deg. Fahr.							
Engine Temperature, deg. Fahr.				86 (30° C.)	68 (20° C.)	50 (10° C.)	32 (0° C.)	−14 (−10° C.	−4 (−20° C.)	−22 (−30° C.)	−40 (−40° C.)
5	20	..	1.301	252	228	205	181	158	135	111	88
6.5	15.4	20	1.284	240	216	193	171	147	125	102	79
7.5	13.3	13	1.2774	237	214	192	169	145	122	99	77
10	10	7	1.27	232	209	187	164	141	119	95	74
25	4	3	1.284	240	216	193	171	147	125	102	79
Average of last four lines.....				237	213	191	168	145	122	99	77

By use of the relationship given in Fig. 1, and the continuous vaporization data on the fuels used in these starting tests, as given in Fig. 4, the resultant air-vapor mixtures formed under equilibrium conditions from the air-fuel ratios supplied at the carburetor were computed and plotted in Fig. 2. The results of this investigation using standard commercial equipment agree within the experimental error with those obtained at the Bureau of Standards using a motor specially equipped and cranked by a dynamometer.

EFFECT OF A.S.T.M. DISTILLATION ON EASE OF STARTING

Although the equilibrium volatility of a fuel cannot be accurately predicted by any simple relationship from the lower end of the distillation curve, the actual starting tests are, however, consistent only within ±20 per cent so that any relationship accurate within these limits should prove satisfactory for all practical purposes.

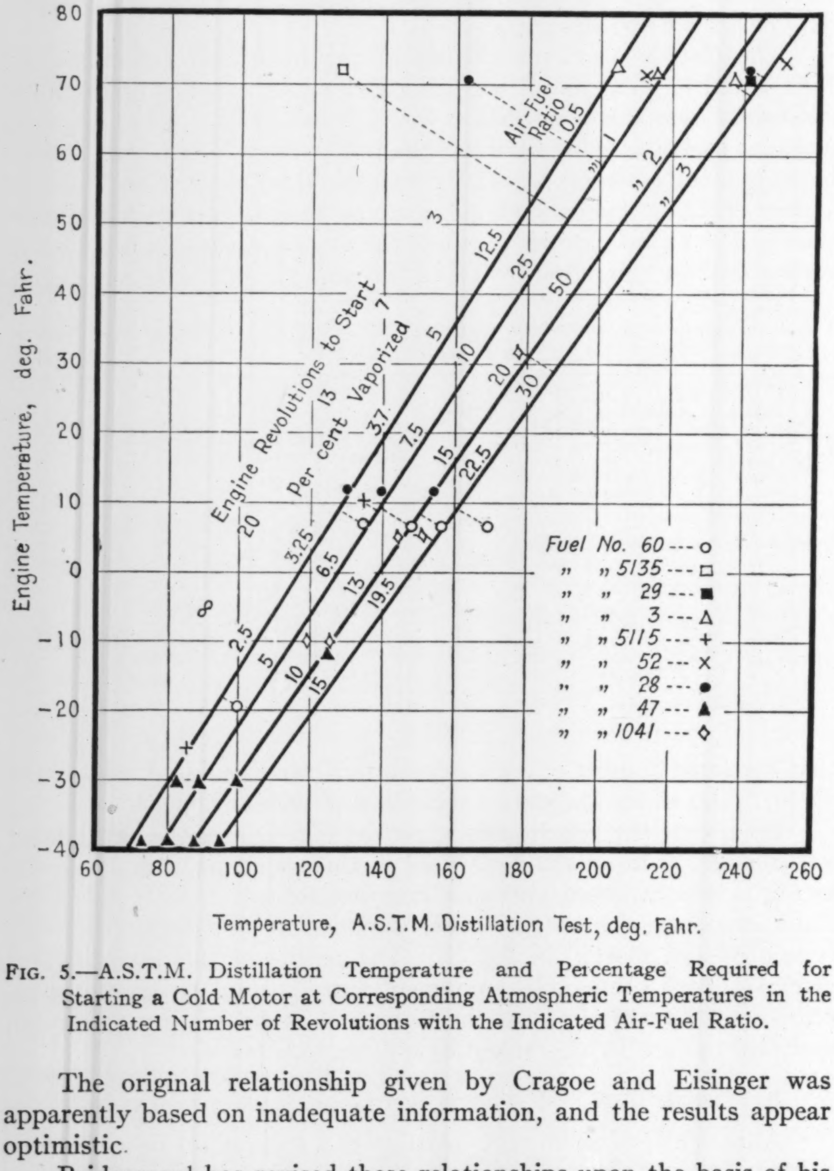

Fig. 5.—A.S.T.M. Distillation Temperature and Percentage Required for Starting a Cold Motor at Corresponding Atmospheric Temperatures in the Indicated Number of Revolutions with the Indicated Air-Fuel Ratio.

The original relationship given by Cragoe and Eisinger was apparently based on inadequate information, and the results appear optimistic.

Bridgeman[1] has revised these relationships upon the basis of his first approximation of the equilibrium-air distillation from the

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[1] *Journal*, Soc. Automotive Engrs., Vol. 22, No. 4, April, 1928, p. 447.

A.S.T.M. distillation. Although the results are probably not as accurate as can be obtained from the equilibrium vaporization curve, they appear well within the experimental error in determining ease of starting with a 1 to 1 air-fuel ratio.

Computations based on these relationships for a 1 to 1 air-fuel ratio give results as shown in Table I. If the resultant air-vapor mixture of 20 requiring approximately an infinite number of revolutions for starting be disregarded as impractical, and only those mixtures which enable the motor to be started in 20 revolutions or less be considered, the A.S.T.M. distillation temperature for 6 to 25 per cent vaporized is practically constant for each engine temperature. If these temperatures are averaged, as has been done in the table, the average A.S.T.M. temperature may be used with an error of less than ±4° F. to indicate all practical degrees of ease of starting at the corresponding engine temperature.

For example, at a temperature of 32° F. the percentage vaporized on the A.S.T.M. distillation at 168° F. may be used to indicate the ease of starting. If 6.5 per cent is distilled at 168° F., the motor may be started in 20 revolutions; 7.5 per cent distilled indicates that the motor may be started in 13 revolutions; 10 per cent distilled at 168° F. indicates that the motor may be started in 7 revolutions; and 25 per cent distilled at 168° F. indicates that the fuel will give a perfect start in three revolutions if a 1 to 1 air-fuel ratio is supplied by the carburetor.

Similar considerations for other air-fuel ratios indicate a similar constancy of temperature on the A.S.T.M. distillation corresponding to particular engine temperatures. These temperatures are plotted for convenience in Fig. 5. For purposes of comparison, actual experimental data obtained with the fuels shown in Fig. 3 are plotted in Fig. 5. Since these points represent actual experimental data, their close agreement with the computed straight lines indicates the accuracy of the relations indicated in Fig. 5.

At low engine temperatures, oil or battery conditions limit the maximum number of revolutions in which a start must be obtained. With a low viscosity oil recommended for cold weather operation the motor could not be cranked at all at a temperature of −10° F. If this oil were diluted to the extent of over 50 per cent only 19 revolutions could be obtained from a fully charged battery at an engine temperature of −20° F. For these reasons it is clear that possible starting at low temperatures demands a fuel so volatile as to start within 10 or 20 revolutions. At higher temperatures 10 or 20 revolutions may be considered an easy start. Furthermore, the lower cranking speed at the low temperature causes a more dilute mixture to be supplied by the carburetor, thereby making starting still more difficult.

EFFECTIVE VOLATILITY UNDER DRIVING CONDITIONS

In considering the vaporization, distribution and combustion of fuel in carbureted internal combustion engines, it is obvious that conditions never reach equilibrium in the intake manifold under driving conditions. For this reason direct comparison between the equilibrium volatility of a fuel as determined in the laboratory and engine acceleration as determined by actual engine tests is impossible. When driving a car at constant speed, a steady state is reached in the intake manifold so that all of the fuel supplied by the carbureter is distributed more or less uniformly to the various cylinders almost regardless of the volatility characteristics of the fuel. During periods of acceleration, particularly with a cool motor or manifold, the amount of fuel delivered to the cylinders immediately after the throttle is suddenly opened is less than that supplied to the manifold by the carburetor.

If the fuel sprayed into the air stream in the carburetor is not completely vaporized, some of the liquid particles settle out of the air stream and deposit on the walls of the manifold, where their progress from the carburetor to the cylinders is much slower than that of the air and vaporized fuel. When the throttle is suddenly opened, the increased air flow reaches the cylinders almost immediately, as does the fuel which is vaporized and carried in the air stream. But the liquid fuel flowing along the walls of the manifold does not reach the cylinders until some time later. As a result of these conditions, the mixture reaching the cylinders immediately after the throttle is opened contains less fuel than that mixture metered by the carburetor into the lower end of the manifold.

In any attempt to determine the relationship between actual engine acceleration or performance and fuel characteristics, the liquid reaching the cylinders and burned in them must be considered as well as the fuel which is vaporized in the manifold. Effective volatility, as defined in this paper, takes these factors into consideration and can be used as a direct indication of motor performance.

The effective volatility of a fuel is defined as the quotient obtained by dividing the air-fuel ratio supplied at the carburetor by the air-fuel ratio burned in the cylinders, immediately after opening the throttle in an acceleration engine test.

From this definition it is evident that the problem of determining the effective volatility of a fuel resolves itself into two simpler problems. The first is that of measuring the air-fuel ratio delivered to the manifold during an acceleration and the second is that of determining the air-fuel ratio burned in the cylinders. The former was measured by special apparatus described in detail elsewhere[1] and the latter by operating the motor under such conditions that the acceleration was dependent only upon the air-fuel ratio burned in the cylinders.

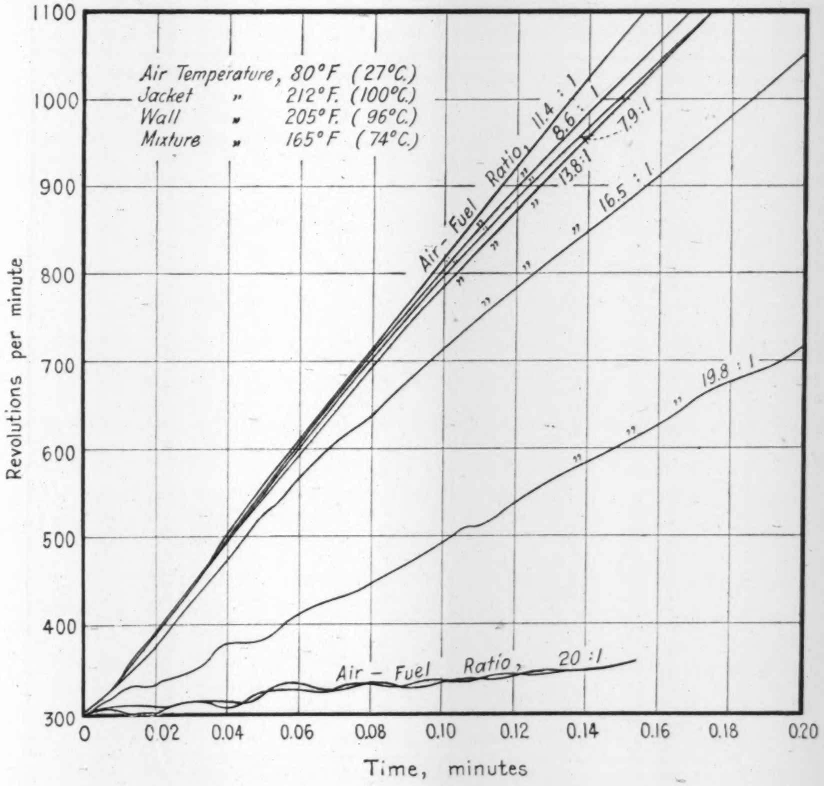

FIG. 6.—Showing the Rate of Acceleration for Fuel No. 24.

The acceleration was determined as a function of the air-fuel ratio burned in the cylinders for each series of tests run on a predetermined schedule by using a "standard" fuel which was completely effectively vaporized under the conditions of the test. When a fuel is completely effectively vaporized, the air-fuel ratio burned in the cylinders is by definition substantially the same as that metered to the manifold. A characteristic set of curves representing this condition with a typical motor gasoline is shown in Fig. 6.

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[1] *Bulletin No. 14*, Department of Engineering Research, University of Michigan, May, 1930.

In order to be sure the "standard" fuel was completely effectively vaporized, fuels more volatile were run at the same manifold temperature. When the accelerations from these fuels were no better than those of the "standard" fuel tested, the "standard" fuel was considered completely effectively vaporized. This conclusion was verified by running accelerations on the "standard" fuel at higher and lower manifold jacket temperatures.

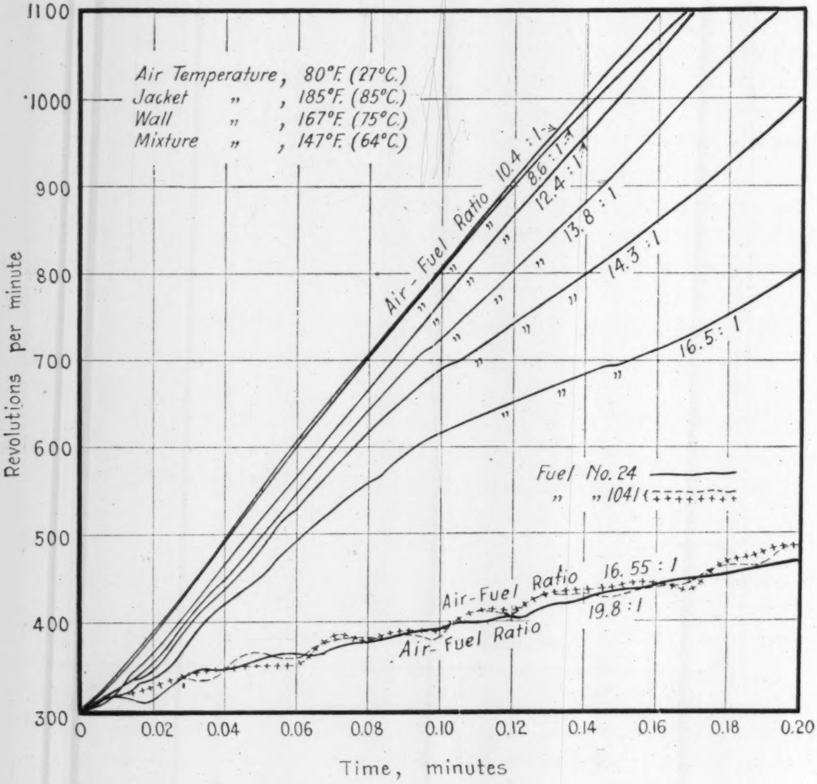


FIG. 7.—Showing the Rate of Acceleration for Fuels Nos. 24 and 1041.

MEASURE OF ACCELERATION

In comparing results of acceleration tests a quantitative measure of acceleration is necessary. The acceleration was taken as the increase in revolutions per minute in the time interval between 0.01 minute and 0.06 minute after the throttle was opened. On the curve for a 19.8 to 1 ratio in Fig. 6, the speed at 0.06 minute is 408 r.p.m., that at 0.01 minute is 310 r.p.m., and the acceleration is recorded as 98 r.p.m.

There were four reasons for choosing the time interval 0.01 to 0.06. In the first place, in an investigation into fuel characteristics an average or integrated value as observed over a finite time interval is preferred to an instantaneous acceleration which varies within wide limits during the course of a single test and is therefore more suited for studying engine variables than fuels which do not change during a test.

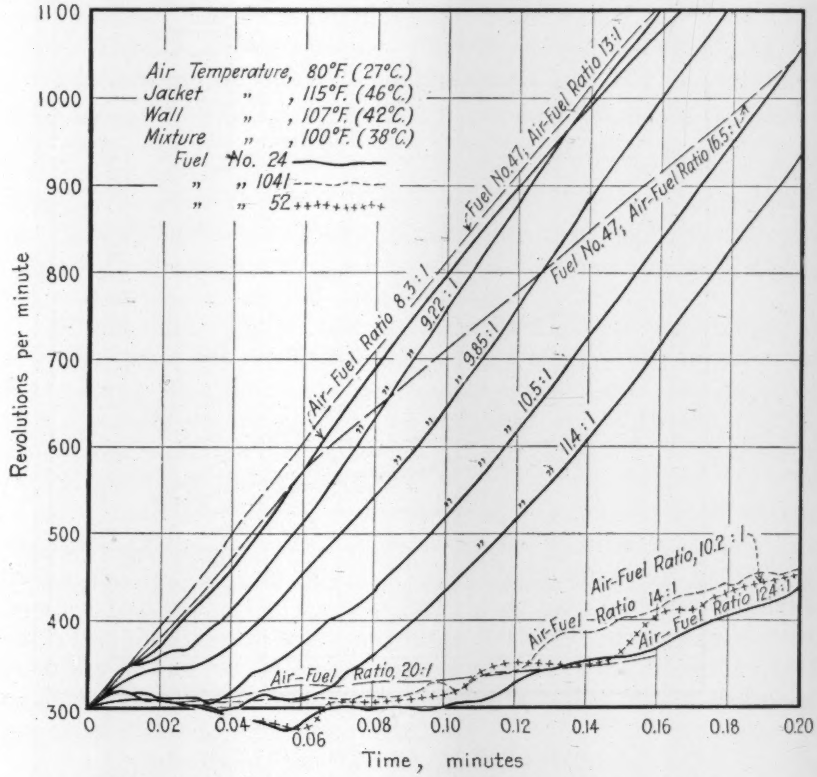


FIG. 8.—Showing the Rate of Acceleration for Various Fuels.

Secondly, the acceleration is about the same for all except high air-fuel ratios during the first 0.005 to 0.01 minute and is, therefore, not a function of air-fuel ratio, or fuel volatility during this time interval. This may be due to the inertia effects in the manifold or in the air valve of the carburetor subsequent to the opening of the throttle. For this reason the acceleration before 0.01 minute should be neglected as it depends largely upon constant manifold conditions and not upon fuel volatility.

Third, when lean mixtures are used, a break in the speed-time curve is frequently observed after about 0.06 to 0.10 minute as shown in Fig. 7. Upon investigation it was found that the mixture temperature decreased during an acceleration. This decreases the effective volatility of the fuel to such an extent that the loss in acceleration is clearly evident in the speed-time curve. For this reason the acceleration following about 0.06 to 0.10 minute should not be included in determining the effective volatility as existing under the initial conditions.

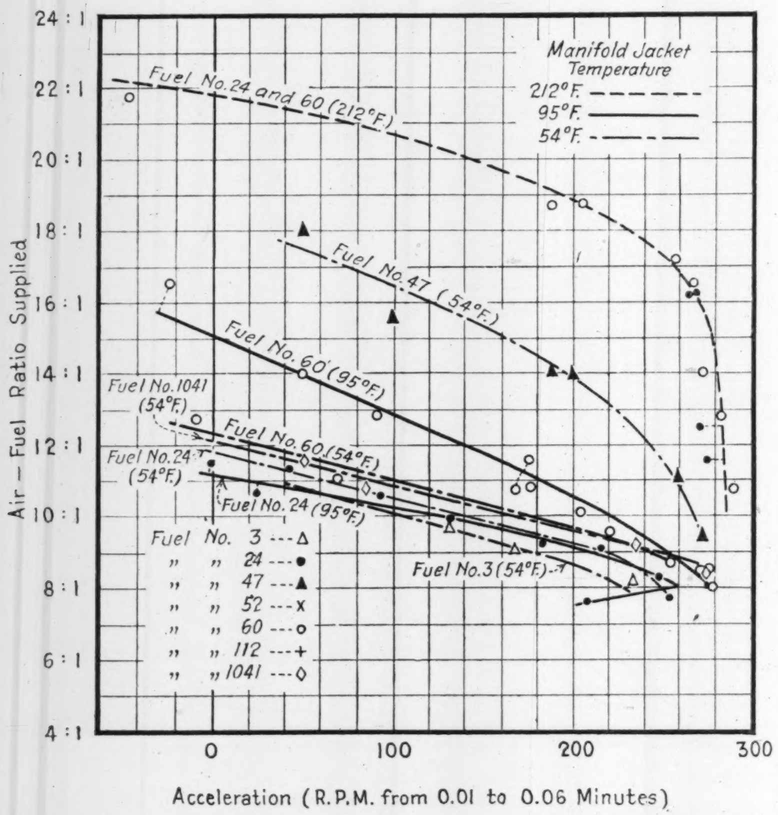


FIG. 9.—Accelerations for Different Fuels Plotted as a Function of Air-Fuel Ratio.

At temperatures considerably below that of complete vaporization, the unvaporized portion of the fuel builds up a film on the manifold walls. The sudden opening of the throttle causes an increase in pressure and further condensation of fuel on the manifold wall. This liquid fuel flows along the manifold wall but at a velocity much less than that of the air stream. When starting an acceleration at 300 r.p.m., about 0.06 to 0.08 minute is required for this additional liquid to reach the cylinders.

This action is evident in Fig. 8. During the first 0.06 or 0.08 minute, which seems to represent the time-lag in distribution of the liquid flowing along the manifold wall, the acceleration is largely determined by the air-fuel ratio since the volatility of the fuel is approximately the same for different air-fuel ratios if the manifold is kept at the same temperature. But after 0.08 to 0.10 minute, the accelerations of the different mixtures from 9.2 to 11.4 are almost identical. An air-fuel ratio of 8.3 contains so much excess fuel that it cannot be burned efficiently and a loss of power results, as is shown by the decreasing slope of the acceleration curve beginning about 0.08 minute after the throttle was opened. The 12.41 mixture did not develop sufficient velocity to distribute the liquid satisfactorily, or possibly the engine temperature was so low that the last 10 to 15 per cent of the fuel did not burn even if distributed.

These data clearly indicate that after about 0.06 minute (4 seconds) conditions in the manifold reach a steady state in which the liquid fuel is distributed to the cylinders at about the same rate that it is deposited on the walls of the manifold, and approximately the same air-fuel ratio is then delivered to the cylinders as is supplied by the carburetor to the manifold.

In Fig. 8 the speed-time curves of a fuel completely effectively vaporized at the indicated temperatures are plotted as dashed lines for 13 and 16.5 air-fuel ratios. The 8.3 ratio curve for fuel No. 24 parallels that of the 16.5 curve of fuel No. 47 from 0.01 to 0.06 minute indicating the same air-fuel ratio burned in the cylinders or an effective volatility of fuel No. 24 under these conditions of 8.1 divided by 16.5, or 49 per cent. At 0.06 minute these curves cross due to conditions not attributable to fuel characteristics.

For these reasons, the "acceleration" was taken as the increase in revolutions per minute during the time interval 0.01 to 0.06 minute. These accelerations were plotted for the different fuels as a function of air-fuel ratio supplied at the carburetor as in Fig. 9.

DETERMINATION OF EFFECTIVE VOLATILITY

Since the acceleration in these tests depends only upon the air-fuel ratio burned in the cylinders, and the acceleration for any air-fuel ratio burned in the cylinders is indicated by the "standard curve";

the air-fuel ratio burned in the cylinders may readily be determined for any fuel, manifold temperature and air-fuel ratio supplied at the carburetor by reading the air-fuel ratio of the "standard curve" giving the same acceleration. For example, in Fig. 9, fuel No. 60, when supplied in an air-fuel ratio of 10.1 at the carburetor and at a manifold jacket temperature of 95° F., gave an acceleration of 205 r.p.m. This is identically the same acceleration obtained when the fuel which is completely effectively vaporized is supplied in an air-fuel ratio of 18.8. This comparison indicates that when fuel No. 60 is supplied in an air-fuel ratio of 10.1 at a manifold jacket temperature of 95° F., the mixture actually burned in the cylinders during the initial stages of acceleration is equivalent to an air-fuel ratio of 18.8 or that 10.1 divided by

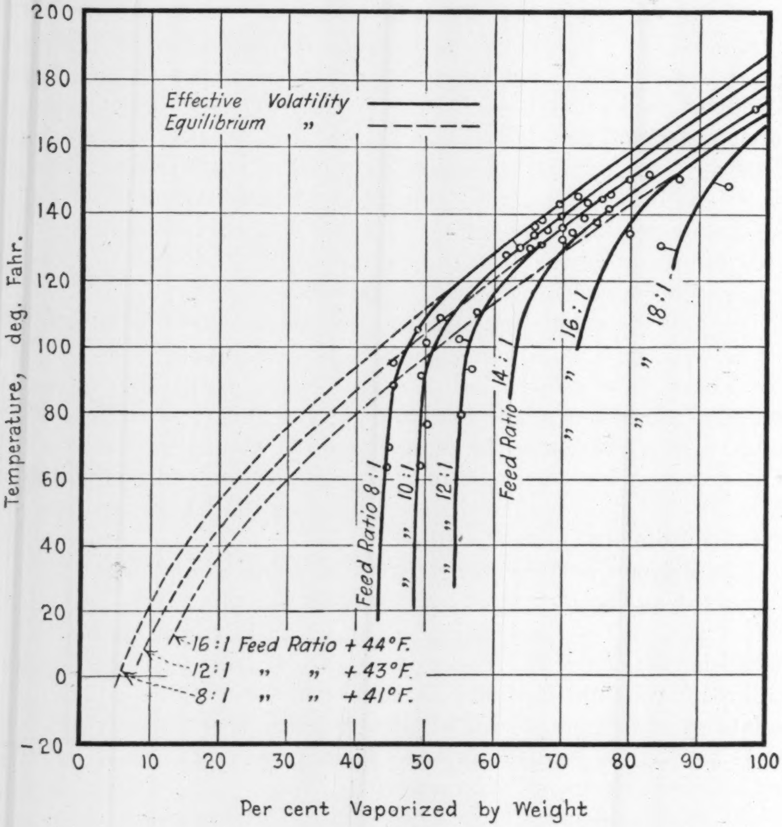


FIG. 10.—The Effective Volatility of a Representative Motor Fuel.

18.8 or 53.7 per cent of the fuel supplied at the carburetor is actually carried to the cylinders and burned in them. Thus, the effective volatility of fuel No. 60 in an air-fuel ratio of 10 with manifold jacket temperature at 95° F. is 53.7 per cent.

However, the effective volatility depends not upon manifold jacket temperature but rather upon mixture temperature. The experimental data clearly indicate that the mixture temperature is dependent not only upon the air and manifold temperatures but also upon the amount of fuel vaporized, which varies not only for the different fuels but also for different mixture ratios with the same fuel. For this reason the initial mixture temperature was plotted as a function of the air-fuel ratio for different manifold jacket temperatures. The temperatures of the mixtures as read from these curves were used in the final plots of effective volatility as shown in Fig. 10.

TABLE II.—RELATIVE EFFECTIVE VOLATILITIES BY ACCELERATION AS IN FIG. 9 AND BY SUPERPOSITION OF ACCELERATION CURVES.

Fuel	Air-Fuel Ratio	Manifold Jacket Temperature, deg. Fahr.	Effective Volatility, per cent	Fuel	Air-Fuel Ratio	Manifold Jacket Temperature, deg Fahr.	Effective Volatility, per cent	Relative Effective Volatilities	
								By Acceleration, Measured in r.p.m. Increase	By Superposition of Acceleration Curves
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
No. 24....	19.8	190	95	No. 1041..	16.5	190	81	0.845	0.83
No. 1041..	14	111	66.5	No. 24....	12.4	111	59.5	0.895	0.885
No. 24....	12.4	111	59.5	No. 52....	10.2	111	48	0.815	0.822
No. 1041..	14	111	66.5	No. 52....	10.2	111	48	0.722	0.730
No. 112...	9.87	111	52	No. 52....	8.8	112	47.5	0.913	0.892
No. 47....	15.3	103	81	No. 60....	14	113	73	0.902	0.915
No. 60....	21.8	212	100	No. 60....	16.65	95	75	0.75	0.765
No. 60....	16.65	212	100	No. 60....	8.58	54	51	0.51	0.515
No. 60....	16.5	95	75	No. 24....	11.5	95	52	0.695	0.696

Limits of Accuracy:

Considerations of the accuracy with which the individual measurements could be made indicate that if all errors are combined in the same direction the individual experimental results should still be accurate to within 6 or 8 per cent in terms of effective volatility. The final results based upon a large number of experimental data are probably accurate to within ±3 per cent, as is indicated by the points in Fig. 12.

As a further check of the accuracy of the effective volatility determined in this manner, the relative effective volatilities of different fuels may be determined by dividing the air-fuel feed ratios required to give practically identical acceleration curves. In fact, this was the method first considered for computing the effective volatility of fuels. Although this plan was abandoned because of the difficulty in obtaining curves which coincided exactly, in those cases where such curves were obtained, as in Fig. 8, the method can be used with results as given in Table II.

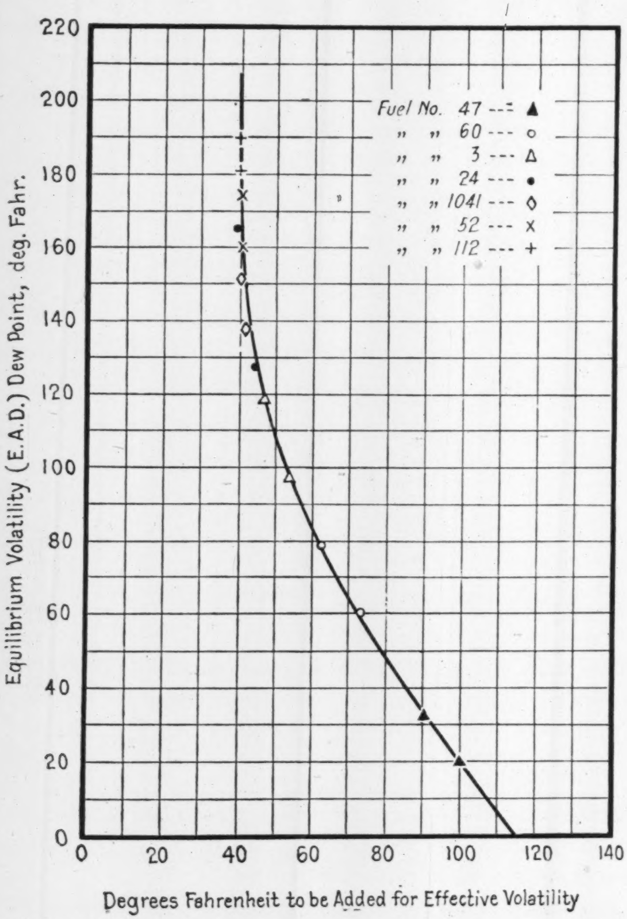


FIG. 11.—Showing the Relation of Equilibrium Volatility to Degrees Fahrenheit Added for Effective Volatility.

In Table II the fuel number, air-fuel ratio, manifold jacket temperature, and effective volatility as determined by the method described above, for two fuels giving acceleration curves which are practically identical, are listed in one line. The relative effective volatilities of the two fuels under these conditions are listed in the last two columns. In column 9 the relative effective volatilities are determined by dividing the effective volatility as determined on the basis of the increase in revolutions per minute between 0.01 and 0.06 minute after the throttle was opened. In column 10 the relative effective volatilities are given as determined by dividing the air-fuel ratios supplied by the carburetor as listed in Table II.

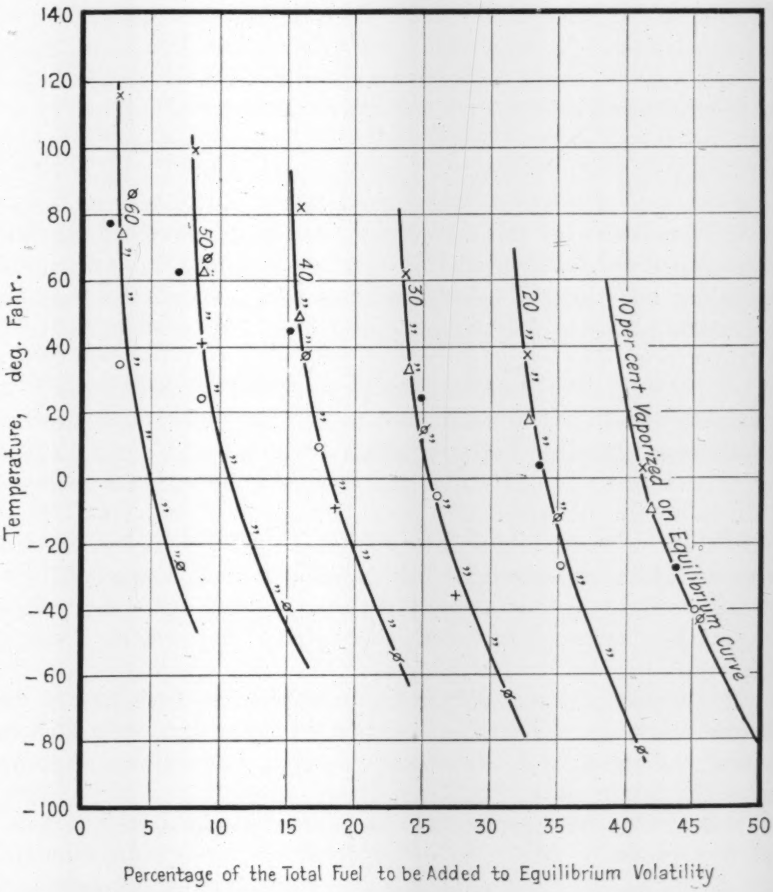


FIG. 12.—Showing Relation of Temperature to Percentage of Total Fuel to be Added to Equilibrium Volatility to Obtain the Effective Volativity for a 12 to 1 Air-Fuel Ratio.

In all cases the relative effective volatilities agree within 2 per cent. In two cases, fuel No. 60 with manifold jacket temperature of 212° F., the comparison is with a fuel of 100-per-cent effective volatility, and the effective volatility as determined by superposition of acceleration curves agrees within 2 per cent of the effective volatility as computed by the increase in revolutions per minute in the manner described above.

This comparison in Table II serves not only as an indication of the probable accuracy of the effective volatility determinations, but also indicates that the acceleration over the 0.01 to 0.06-minute interval gives a value for the effective volatility of the fuel which is of significance throughout the entire acceleration period.

EFFECTIVE VOLATILITY RELATED TO EQUILIBRIUM VOLATILITY

The effective volatility curves, such as in Fig. 10, appear to have little in common with the equilibrium volatility curves of the same fuels as reported by Brown and Skinner. Reasoning that the equilibrium is not reached in the manifold of a motor because of the short time interval allowed for vaporization, it seemed quite evident that the temperature of complete effective volatility would be higher than the dew point or temperature of complete volatility under equilibrium conditions, and might be estimated by adding some number, yet to be determined, to the corresponding dew point. In order to make this comparison and to determine a relationship by which the effective volatility might be estimated from the equilibrium volatility, the temperature of each equilibrium volatility curve as computed from the equilibrium vaporization has been increased throughout by a constant amount so that as plotted the dew point coincides with the corresponding temperature of complete (100-per-cent) effective volatility.

It was found that a different number had to be added to each different dew point. These numbers added to the dew point to obtain the temperature of complete effective volatility are plotted as a function of the dew point in Fig. 11.

It is clear that a greater number must be added to low than to high dew points. This is to be expected since reactions take place more slowly at lower temperatures, and the difference between actual and equilibrium conditions in the manifold will be greater at low temperatures. Comparison of the modified equilibrium and effective volatility curves as in Fig. 10 indicate that these curves coincide throughout only the upper range. For less than 50 to 70 per cent vaporized the effective volatility curve falls away from the modified equilibrium curve, indicating a relatively greater effective volatility.

This difference may be due to the existence of a thicker liquid film on the manifold walls when the fuel is less volatile, so that a considerable proportion of the fuel is distributed as liquid along the manifold walls to the cylinders immediately after the throttle is opened, but the exact reason is not clear as the method of relating effective and equilibrium volatilities is largely empirical.

In Fig. 12 this liquid distribution expressed as a percentage of the total fuel, to be added to the equilibrium volatility, is plotted as a function of the corresponding equilibrium temperature. At lower temperatures the liquid distribution becomes larger. This is probably due to the combined effect of the greater density of vapor being able to carry more mist, and the greater viscosity of the fuel which allows a thicker film to be maintained on the walls of the manifold during the idling period previous to opening the throttle for an acceleration. The liquid fuel distributed to the cylinders by means of a film flowing along the manifold walls during the idling period, is also similarly distributed during the first 4 seconds (0.06 minute) after the throttle is opened or until the liquid fuel forming the new film can reach the cylinders.

This method of estimating the effective volatility of fuels is tedious. It would be far more convenient if the effective volatility could be estimated directly from the A.S.T.M. distillation even with some loss in accuracy.

EFFECTIVE VOLATILITY FROM THE A.S.T.M. DISTILLATION

Comparison of the A.S.T.M. and continuous distillation curves as shown in Figs. 3 and 4 indicate that they cross at approximately the same percentages in either distillation. Therefore, the A.S.T.M. percentages may be considered as equivalent to the equilibrium volatility percentages, but at different temperatures. Since both temperature and percentage vaporized in the equilibrium volatility must be modified to obtain the effective volatility, the latter can be estimated directly from the A.S.T.M. distillation by applying proper temperature and percentage corrections directly to the A.S.T.M. distillation data.

If the motor is to be driven without use of the choke, the effective volatility of the fuel must be sufficient to deliver at least an explosive mixture to the cylinders under all conditions of operation. Assuming that the carburetor is adjusted to deliver a 12 to 1 air-fuel ratio, and that a 20 to 1 air-fuel ratio is the leanest mixture that can be exploded in the engine, it is evident that the effective volatility of the fuel must be not less than 60 per cent if the motor is to be kept running. The experimental data indicate that the effective volatility in a 12 to 1 mixture ratio is about 60 per cent when apparently 58 per cent of the fuel is actually vaporized. Since the 58-per-cent point on the equilibrium volatility curve may be related approximately to the 58-per-cent point on the A.S.T.M. distillation curve, the latter may be used to indicate the minimum temperature of the mixture at which the car could be operated without use of the choke, provided the carburetor supplies an air-fuel ratio of about 12 to 1.

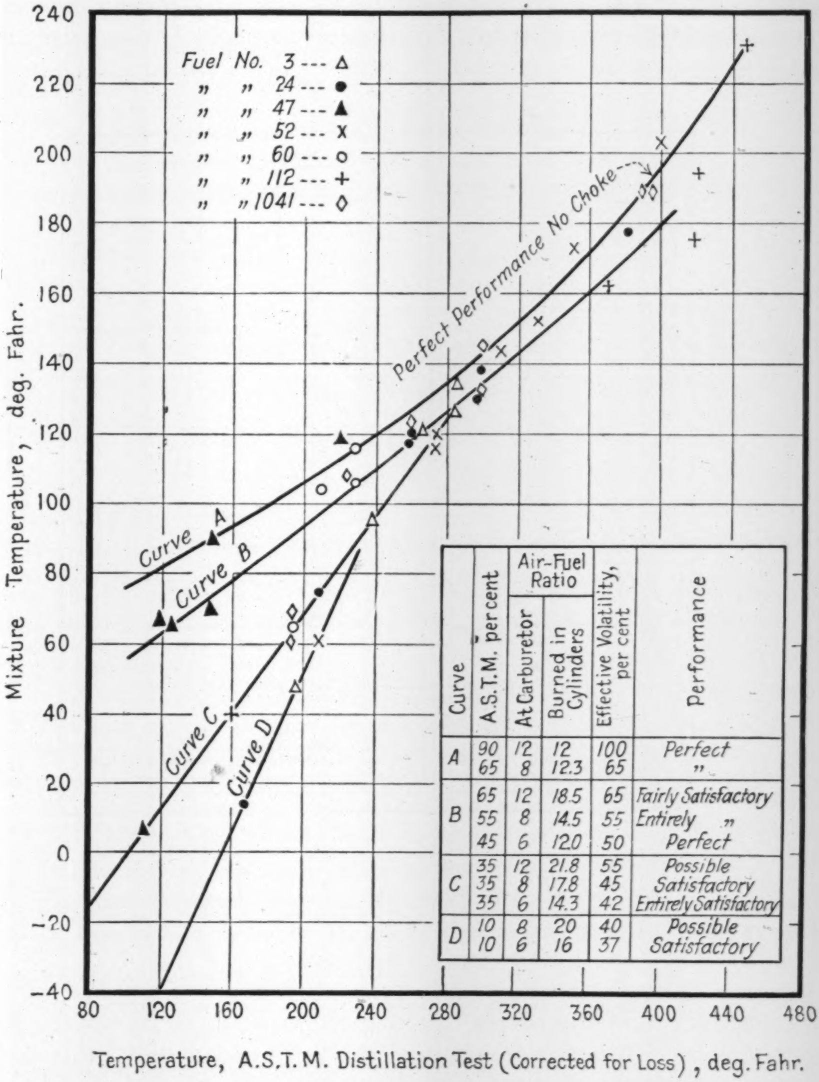
Most modern cars are equipped with carburetors supplied with accelerating devices which inject an additional charge of fuel into the manifold whenever the throttle is suddenly opened. The effect of these accelerating charges is to deliver a mixture ratio of approximately 8 to 1 during the early stages of the acceleration when the carburetor is adjusted to supply a 12 to 1 air-fuel ratio under steady conditions. With an air-fuel ratio of 8 to 1, 55-per-cent equilibrium volatility appears to correspond directly to 55-per-cent effective volatility, or an air-fuel ratio of about 14.5 supplied to the cylinders. A mixture ratio of 14.5 is sufficiently rich to give satisfactory acceleration. But for maximum power a mixture ratio of about 12.3 is required, which corresponds to an effective volatility of about 65 per cent in a feed ratio of 8 to 1.

If at the operating temperature the fuel does not possess sufficient effective volatility to give satisfactory acceleration performance, the driver will resort to the choke in order to obtain better throttle response. If the choke is used to enrich the mixture, or the carburetor adjusted to deliver an 8 to 1 air-fuel ratio under steady conditions, an effective volatility of about 45 per cent would give practically perfect throttle response on cars equipped with accelerating devices and supplying approximately a 5.4 mixture ratio during the first stages of the acceleration period, and fairly satisfactory response with cars not so equipped.

Figure 13 indicates the mixture temperature, as measured by a thermocouple in the air stream in the intake manifold near the engine block, required to give the indicated effective volatility, as a function of the A.S.T.M. distillation data. It also indicates the quality of throttle response for various mixture ratios supplied by the carburetor at the indicated mixture temperature and when using fuels of known distillation characteristics.

If the fuel does not possess 40-per-cent effective volatility, it becomes practically impossible to drive with one choke setting unless the car is equipped with accelerating devices. Even then an effective volatility of at least 30 per cent is necessary. Apparently the 30 to 40-per-cent effective volatility is related to the 10-per-cent equilibrium volatility or the 10-per-cent point on the A.S.T.M. distillation as indicated by curve *D*.

Not only is it important that the 10, 35, and 65-per-cent points on the A.S.T.M. distillation be sufficiently low to allow the car to be operated in a satisfactory manner during the warming up period and at reasonably low manifold temperatures, but if the 90-per-cent point is too low and the fuel is completely vaporized at the mixture temperature existing in the manifold, loss in power and increased fuel con-



Curve	A.S.T.M. per cent	Air-Fuel Ratio		Effective Volatility, per cent	Performance
		At Carburetor	Burned in Cylinders		
A	90	12	12	100	Perfect
	65	8	12.3	65	"
B	65	12	18.5	65	Fairly Satisfactory
	55	8	14.5	55	Entirely "
	45	6	12.0	50	Perfect
C	35	12	21.8	55	Possible
	35	8	17.8	45	Satisfactory
	35	6	14.3	42	Entirely Satisfactory
D	10	8	20	40	Possible
	10	6	16	37	Satisfactory

FIG. 13.—Showing Mixture Temperature Measured by a Thermocouple.

sumption may result if the car is equipped with acceleration devices. If the carburetor is adjusted to supply a 12 to 1 air-fuel ratio at all times, a fuel that is completely vaporized would give the maximum power; but if the carburetor is equipped with accelerating devices a mixture ratio of about 8 to 1 or in some cases 6 to 1 is supplied to the cylinders during the accelerating period when a mixture of 12 to 1 is required. This excessively rich mixture causes a loss in power and acceleration. Although frequently observed in road tests,[1] this fact has been generally overlooked in discussions of motor fuel quality as related to the modern automobile.

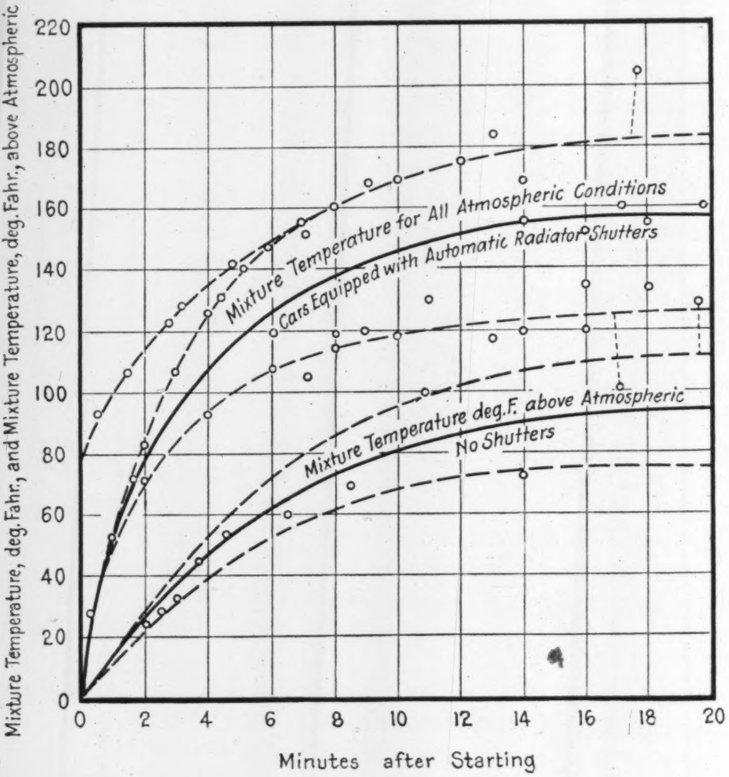


FIG. 14.—Mixture Temperatures for Different Types of Motors and Under Different Driving Conditions.

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[1] Adrian Hughes, Jr., *Journal*, Soc. Automotive Engrs., Vol. 26, No. 1, January, 1930, p. 49.

VOLATILITY RELATED TO ENGINE PERFORMANCE

These conclusions derived from careful tests on one motor with special fuel metering equipment, have been verified by extensive road and laboratory tests using fuels such as shown in Fig. 3. In order to estimate the distillation characteristics desirable for different atmospheric temperatures, mixture temperatures were recorded for different types of motors and under different driving conditions.[1] Figure 14 gives in graphical form the results of these tests for modern motor cars equipped with radiator shutters and efficient manifold heating and also for motors not so equipped.

TABLE III.—RELATION BETWEEN A.S.T.M. DISTILLATION AND MOTOR PERFORMANCE AT DIFFERENT ATMOSPHERIC TEMPERATURES.

Atmospheric Temperature, deg. Fahr.[b]	For modern motor car equipped with exhaust-heated manifold hot spot, carburetor with effective accelerating device, and radiator shutters.								For car not equipped with radiator shutters, and supplying less heat to the intake manifold, or with carburetor which supplies only a limited accelerating charge.						
	10-per-cent Temperature Points on A.S.T.M. Distillation,[a] deg. Fahr.		35-per-cent Temperature Points on A S.T.M. Distillation,[a] deg. Fahr.		60-per-cent Temperature Points on A.S.T.M Distillation,[a] deg. Fahr.		90-per-cent Temperature Points on A.S.T.M. Distillation,[a] deg. Fahr		10-per-cent Temperature Points on A S.T.M. Distillation,[a] deg. Fahr.		35-per-cent Temperature Points on A.S.T.M. Distillation,[a] deg. Fahr.		65-per-cent Temperature Points on A.S.T M. Distillation,[a] deg. Fahr.	90-per-cent Temperature Points on A.S.T.M. Distillation,[a] deg. Fahr.	
	Minimum[c]	Maximum[d]	½ Minute[e] After Starting	2 Minutes[f] After Starting	4 Minutes[g] After Starting	8 to 10 Minute[h] After Starting	Minimum[j]	Maximum[k]	Minimum[c]	Maximum[d]	½ Minute[e] After Starting	4 Minutes[f] After Starting	10 Minutes[i] After Starting	Minimum[j]	Maximum[k]
80	140	230	235	275	275	320	390	450	135	230	235	280	300	320	450
50	125	190	200	250	260	310	375	420	115	190	190	240	260	250	410
20	110	150	175	230	235	290	350	400	100	150	150	200	200	180	390
−10	90	100	125	210	180	280	320	400	85	100	100	160	120	120	370

[a] With loss added at lower end.
[b] Average atmospheric temperature in which the cold motor is started and operated.
[c] The lowest 10-per-cent temperature consistent with easy starting of cold motor, and freedom from vapor lock with hot motor.
[d] The highest 10-per-cent temperature which allows starting and warming up without difficulty under average conditions.
[e] The maximum 35-per-cent temperature which allows possible to fairly satisfactory operation without choking about ½ minute after starting, or entirely satisfactory performance with the use of the choke.
[f] The maximum 35-per-cent temperature which allows similar operation at time intervals indicated.
[g] The maximum 60-per-cent temperature giving almost perfect performance without choking about 4 minutes after starting.
[h] The maximum 60-per-cent temperature giving perfect performance without choking about 8 to 10 minutes after starting.
[i] The maximum 65-per-cent temperature giving perfect performance without choking about 8 to 10 minutes after starting.
[j] The minimum 90-per-cent temperature not causing loss in acceleration on warm motor.
[k] The maximum temperatures of 90-per-cent now known to be satisfactory under indicated conditions.

By combining the information contained in Figs. 13 and 14 it is possible to estimate with sufficient accuracy for all practical purposes the A.S.T.M. distillation characteristics required in a fuel to give any desired quality of throttle response on automotive equipment now in use.

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[1] For complete data, see *Bulletin No. 14*, Department of Engineering Research, University of Michigan, May, 1930.

VAPOR LOCK

Some cars heat the liquid fuel as well as the vapor to high temperatures and experience difficulty due to vapor lock when using fuels of high vapor pressure. Extensive road tests with cars susceptible to this trouble indicate that the probable maximum liquid fuel temperature may be represented by the following expression:

Maximum Fuel Temperature, deg. Fahr. = 100 + $\frac{1}{2}$ Atmospheric Temperature, deg. Fahr. The tendency of a fuel to form vapor and cause trouble due to vapor lock is measured directly as its vapor pressure. The temperature at which 10 per cent is vaporized in the A.S.T.M. distillation may be taken as a fair approximation of the temperature at which the vapor pressure of the fuel is equal to atmospheric pressure. For this reason the safe minimum 10-per-cent temperature in degrees Fahrenheit may be taken as equal to

$$100 + \frac{\text{Atmospheric Temperature}}{2}.$$

A.S.T.M. DISTILLATION CHARACTERISTICS IN TERMS OF ENGINE PERFORMANCE

By combining this information on vapor lock with that incorporated in Figs. 5, 13 and 14, it is possible to suggest the A.S.T.M. distillation characteristics required of motor fuels to give the desired quality of throttle response. This has been done in Table II for the two extreme types of motor vehicles now in common use.

The differences in the fuel requirements of different motors are due largely to differences in mixture temperature and in carburetor metering characteristics rather than in the distributing characteristics of the manifold. For this reason, data such as suggested in Table III may readily be computed by anyone from a knowledge of the air-fuel ratio supplied by the carburetor, the mixture temperature and the data given in Figs. 5 and 13.

DISCUSSION

Mr. S. Tijmstra.[1]—In order to use Fig. 1 of the paper, it is necessary to know the relation between the vapor pressures at different temperatures. I should like to ask Mr. Brown which expression for this relation he uses. We are using the Cox curves but we find that they are not entirely satisfactory.

Mr. G. G. Brown.[2]—The vapor pressure relationships we used were some that were worked out about three years ago and were published as *Circular No. 2* of the Department of Engineering Research of the University of Michigan. We have been working on the wider ranges, ranges up through C_{22}. The data for the higher molecular weights are so limited that the extended chart has not been published. I believe this chart, Fig. 1, will work out equally well with any vapor pressure relationship. The Cox chart is very convenient and should be satisfactory, although I believe the other relationship I referred to is more accurate.

Mr. T. G. Delbridge.[3]— Mr. Brown stated that high-test gasolines might be accompanied by low power output. I should like to ask that he explain what he means by a high-test gasoline.

Mr. Brown.—High-test was, perhaps, an unfortunate expression. Fuels with 90-per-cent points so low that the fuel is actually completely vaporized may be accompanied by a low power output.

I used the term "high-test" to indicate an aviation type of gasoline of high gravity. But we also have high gravity gasolines with fairly high 90-per-cent points and "high-test" is used, occasionally, when referring to any premium gasoline.

In this discussion I have used "high-test" to indicate low 90-per-cent points, and not in any way high compression or anti-knock fuels.

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[1] Technical Assistant, Manufacturing Dept., Shell Petroleum Corp., St. Louis, Mo.

[2] Professor of Chemical Engineering, University of Michigan, Ann Arbor, Mich.

[3] Process Supervisor, The Atlantic Refining Co., Philadelphia, Pa.

THE COMPARATIVE STRENGTH OF SHORT WOODEN BEAMS WITH AND WITHOUT OVERHANG BEYOND THE SUPPORTS

By F. J. Converse[1]

Synopsis

The purpose of this investigtion was to determine whether the overhang of a wooden beam beyond the supports would affect the resistance of the beam in longitudinal shear.

In all cases where the load was applied parallel to the grain of the wood, and was so distributed as to prevent crushing of the fibers under the load and at the supports, the tests indicate that the overhang has little effect upon the strength in shear. Whenever much crushing occurred at the supports and under the load, the breaking load was in general higher for the beams with overhang than for those without.

The elastic line of short beams with overhanging ends reverses its direction of curvature near the inside edge of the supports and becomes concave downward for a short distance before becoming a straight line in the overhanging portion of the beam.

The statement is frequently heard among designing engineers, and has also appeared in technical literature, that beams weak in horizontal shear can be strengthened by adding material beyond the support. The fact that there seems to be no theoretical basis for such an assumption led to the following series of experiments.

Materials and Methods

The timber for test was obtained in the local market in long lengths, surfaced at the mill and cut to size as shown in Table I. The materials used were Douglas fir, spruce, redwood, and oak. Long pieces of timber were cut into specimens of two different lengths. The short ones were equal to the span plus the width of the bearing plate, except in series No. 4 where they extend 2 in. beyond the supports, while the longer ones extended beyond the supports from five to seven inches. In cutting the test specimens from the long sticks, short specimens and long specimens were taken alternately.

The tests were made on a Riehlé 30,000 lb. universal testing machine having a least reading of 10 lb. and being sensitive to 5 lb.

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[1] Instructor in Mechanics, California Institute of Technology, Pasadena, Calif.

Load was applied uniformly by power at the rate of 0.14 in. per minute.

Load was applied at two points symmetrically located with respect to the center line. Both load and reactions were distributed by means of steel plates and felt pads. In most cases only readings of maximum load were taken but in several instances extensometers were used to determine the elastic line. Figure 1 shows the method of applying the load and distributing the reactions.

TABLE I.—SIZE OF TEST SPECIMENS.

	Kind of Timber	Number of Specimens	Length of Original Stick, ft.	Cross-Sectional Dimensions, in.	Length of Test Specimens, in.		Span, in.
					Long	Short	
Series No. 1	Douglas Fir	8	16	1.66 by 3.53	28	18	16
Series No. 2	Douglas Fir	8	16	1.66 by 3.53	30	18	14
Series No 3	Douglas Fir	8	16	1.65 by 3.45	30	18	14
Series No. 4	Spruce	6	12	1.64 by 3.52	30	18	12
Series No. 5	Spruce	10	16	1.62 by 3.50	23	11	9
Series No. 6	Redwood	12	10	2.25 by 2.25	23	11	9
Series No. 7	Oak	8	6	1.80 by 1.80	25	11	9

In the tests to determine the elastic line, small brads were driven along the intersection with the sides of the specimen of the original horizontal central plane, at 1-in. intervals. Dial gages reading to thousandths of an inch were mounted on the weighing table and attached to the brads by fine wire. Load was applied at the same rate as before but was held at each increment long enough to read the gages. Curves of load and deformation were plotted and the zero correction of deformation obtained. The corrected deformations were then plotted, giving the elastic line.

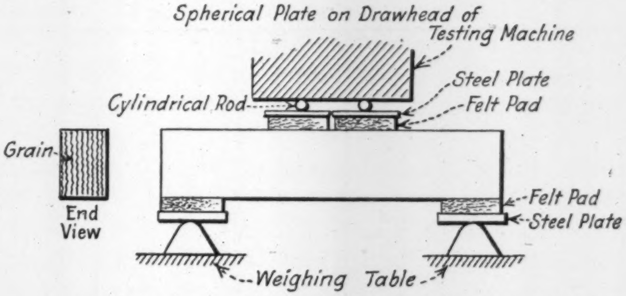

FIG. 1.—Showing Method of Applying Load and Distributing Reactions.

DATA AND DISCUSSION

Figure 2 shows the test results in mass form. Each series represents the tests of one stick, the specimens being taken from left to right in the order of their positions in the stick. The shaded portions indicate beams with overhang. Groups (*a*) and (*b*) of series No. 7

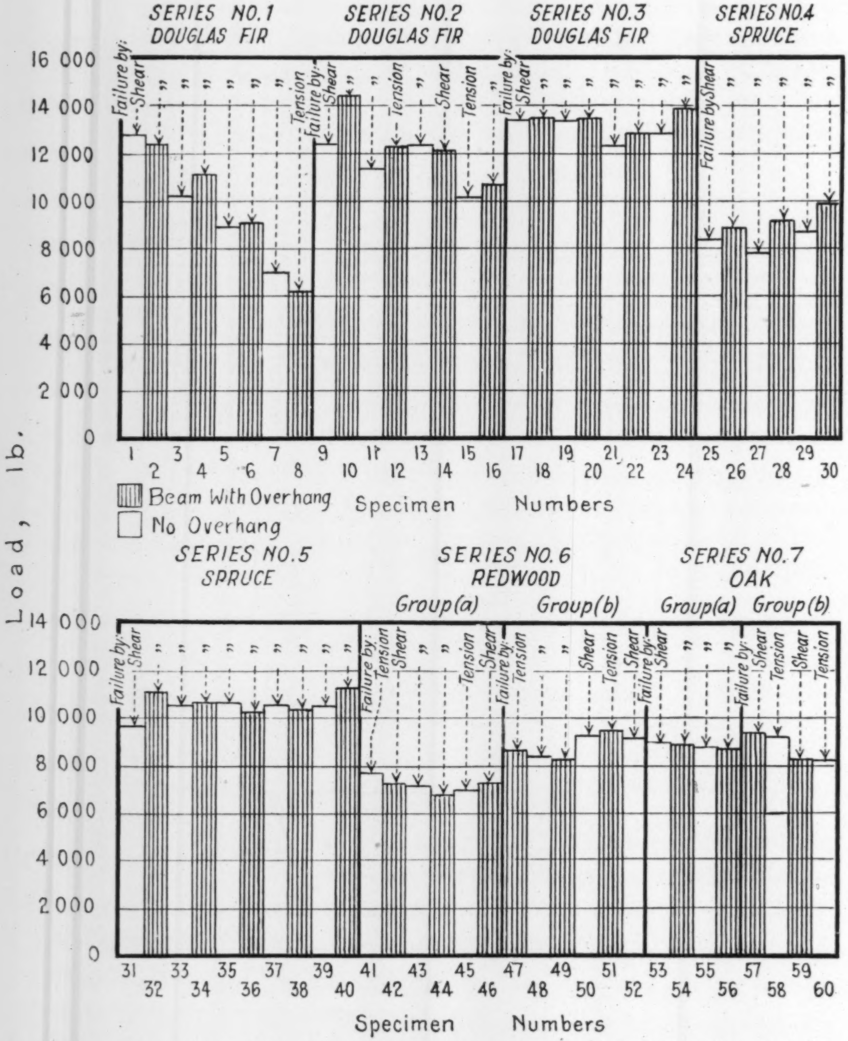

FIG. 2.—Showing Test Results of Specimens Nos. 1 to 60 in Series Nos. 1 to 7, with Cause of Failure Indicated.

represent adjacent sticks ripped from the same board. The same is also true of groups (*a*) and (*b*) of series No. 6.

The test specimens of series Nos. 1 and 4 and also specimens Nos.

57 and 58 of series No. 7 were loaded perpendicular to the grain. The others were loaded parallel to the grain.

There was considerable crushing of the fibers under the load and over the supports on all of the specimens loaded perpendicular to the grain, but by far the worst crushing occurred in the specimens of series Nos. 1 and 4. In the case of the spruce (series No. 4) the excessive crushing caused the overhanging ends to split, opening up cracks as much as $\frac{3}{4}$ in. wide at the ends of the beam before the final shear failure occurred. This splitting was due to induced tension perpendicular to the grain and not to shearing. While there was considerable crushing in the Douglas fir specimens Nos. 17 to 24 (series No. 3), it was not so bad as that in the other 16 specimens of that material.

Four of the nine sticks tested show shear breaks for all specimens. Of these sticks the spruce of series No. 4 crushed excessively over the supports and under the load. The spruce of series No. 5 and the oak of series No. 7, group (*a*), showed practically no crushing of the fibers. In the Douglas fir specimens, series No. 3, there was considerable crushing. These last three series show fairly uniform strength in shear throughout the length of the stick.

Observation of these figures shows that there is no definite increase in shearing strength due to overhang where excessive crushing is not present. Observation of the figures is probably of more value in this case than a consideration of averages. The average strength of the overhanging beams of series No. 3 is 2.26 per cent higher than that of the short ones. Most of this advantage is due to specimen No. 24.

The average strength of the overhanging beams of series No. 5 is 3.3 per cent higher than that of the short ones. Here again the higher strength does not represent consistently higher values for all overhanging specimens of the group but is due to the exceptionally high values of specimens Nos. 32 and 40. Specimens Nos. 36 and 38 have lower values than four of the short specimens.

The two oak specimens with overhanging ends, Nos. 54 and 56, averaged 0.39 per cent lower than the two short beams of that group.

The two short specimens of oak of series No. 7, group (*b*), both broke in tension. It is probable that their strength in shear was not much greater. The overhanging beams had an advantage of 1.93 per cent in this case.

Of the redwood specimens of series No. 6, group (*a*), two of the short beams broke in tension. The average strength of the long beams was 2.25 per cent lower than the short ones. Several of the specimens of series No. 6, group (*b*), broke in tension. The average strength of the overhanging beams was 1.6 per cent less than that of the short ones.

The spruce beams shown of series No. 4 all give a lower total load than those of series No. 5. It is probable that the splitting of the ends as mentioned above is responsible for this. The splitting probably affected the short beams more than the long ones, for the average load of the short beams is 10.62 per cent less than that of the long ones. The fact that nearly all of the beams in which excessive crushing occurred failed in shear first at points near the top or bottom of the specimen rather than at the neutral axis, may indicate that the crushing affected the strength of the beams.

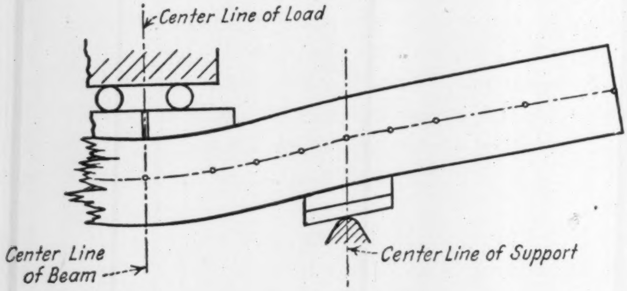
Center Line of Load
Center Line of Beam
Center Line of Support

FIG. 3.—Showing Curve of Neutral Surface for Loads Less Than Maximum. (Vertical scale 10 times horizontal.)

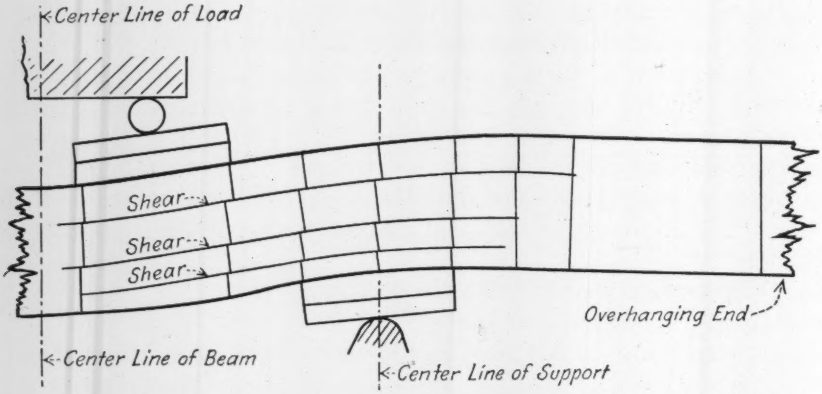
Center Line of Load
Shear
Shear
Shear
Overhanging End
Center Line of Beam
Center Line of Support

FIG. 4.—Half of Oak Beam After Failure.

The vertical lines shown broken at the shear planes were originally straight lines drawn on the side of the beam perpendicular to the neutral surface.

In both series Nos. 1 and 2 of Douglas fir specimens, not only crushing occurred but there were also some failures in tension, so that little reliability can be placed on average strengths of these groups. The average strength of the long specimens of series No. 1 was 0.42 per cent lower than that of the short ones, while in series No. 2 the long ones were 6.9 per cent stronger than the short ones.

The first shear failure in the overhanging beams always occurred in the portion of the beam between the supports and the load. In some cases further deformation, at a reduced load, caused the beam to shear through to the end, while in other cases the second failure was in tension at the center of the beam, leaving the overhanging end unbroken.

Figure 3 shows a typical example of the elastic line of these beams. The reversal of curvature over the supports is quite evident. The shape of this curve is probably due to the fact that the shearing deformation is large compared to the deformation due to bending.

Figure 4 is an example of an overhanging beam after failure by shear. Shear has occurred along three planes. The amount of shearing deformation is shown by the breaks in the vertical lines. These lines were originally drawn on the side of the beam as straight lines perpendicular to the neutral surface.

The end of the overhanging beam in this case actually drops below the original position of the neutral surface.

CONCLUSIONS

1. Extending beams beyond the support is of no value in preventing failure by longitudinal shear in beams in which there is no crushing under the loads or over the supports.

2. The elastic line of short beams with overhanging ends reverses its direction of curvature near the inside edge of the supports and becomes concave downward for a short distance before becoming a straight line in the overhanging portion of the beam.

THE TESTING OF CONDENSER PAPER

By F. L. Roman[1]

Synopsis

This paper discusses the relationship between several characteristics of condenser paper made from linen stock and the dielectric strength (breakdown voltage) of the condensers wound with this paper. Condenser papers 0.0004 and 0.0005 in. in thickness, from foreign as well as domestic sources, are included in this study.

The conclusion is reached that variations in the density of the condenser paper have no noticeable effect on the dielectric strength of the corresponding condensers. It is shown that, when in small numbers, conducting paths through the paper have no important effect on the dielectric strength of condensers wound with two sheets of the paper between tinfoils, but that the percentage of "shorted" condensers or of condensers failing at very low voltages may be expected to increase approximately as the square of the number of conducting paths per unit area of the paper.

Variations in the porosity of the paper are shown to have marked influence on the dielectric strength of the corresponding condensers and porosity requirements for papers used in low-voltage condensers and for papers used in high-voltage condensers are suggested.

Introduction

The quantity of condenser paper used by the radio and telephone industries has been increasing rapidly within recent years and there are a number of manufacturers who each uses several hundred thousand dollars worth of condenser paper annually. It is desirable, therefore, that adequate methods of checking the quality of the condenser papers be established.

Although some of the characteristics of the condenser papers, such as density, porosity and number of conducting paths per unit area, are now controlled by tests, the relation between these characteristics and the characteristics of the corresponding condensers is not generally understood. Most of the condenser manufacturers still find it necessary to make shop trials to determine whether condensers of the desired dielectric strength can be produced with these papers. The process of manufacturing condensers is, however, subject to many variables, and when the condensers produced are of poor dielectric strength it is often questionable whether the dielectric material or the process of manufacture is at fault.

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The condensers are wound with two or more sheets of paper between sheets of tinfoil or aluminum foil, the number of sheets of paper used depending on the voltage the condensers must withstand. Papers made from linen stock are commonly used, and all the data and suggestions for requirements in this paper are given with reference to papers of this type. The condenser units are dried, impregnated and potted and in some cases formed or pressed at various stages of the process. Variations in winding, in period, temperature and reduced pressure used during drying and impregnation, in pressures and temperatures at time of pressing, in temperature during potting, in time elapsed between the various operations, all affect the dielectric strength of the condensers produced.

It will readily be seen that methods of test other than a shop trial are highly desirable as a means of determining whether the paper is capable of producing condensers of a specified minimum dielectric strength.

TABLE I.—DIELECTRIC STRENGTH OF CONDENSER PAPERS AND OF CORRESPONDING CONDENSERS.

	Breakdown Voltage of 0.0004-in. Condenser Paper, volts (Alternating Current)											Average Breakdown Voltage of 1-mfd. Condensers, Using Two Sheets of Paper Between Tinfoils, volts (Alternating Current)
	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5	Sample No. 6	Sample No. 7	Sample No. 8	Sample No. 9	Sample No. 10	Average	
Lot No. 4T...	500	425	500	500	490	490	515	520	515	505	496	655
Lot No. 2T...	490	490	290	275	500	490	485	495	500	500	451	679
Lot No. 7T...	500	500	515	515	515	515	520	520	505	505	511	954
Lot No. 5T...	520	520	535	525	530	520	525	525	535	520	525	1024
Lot No. 1620T	590	570	590	780	560	630	560	730	630	620	626	1603

DIELECTRIC STRENGTH

The difference between the dielectric strength of the poor-grade papers which produce condensers of low breakdown voltage and the dielectric strength of the high-grade papers which produce condensers of high breakdown voltage is small, as may be seen from Table I. The papers listed in the table were conditioned together. They were dried for one hour at 105 to 110° C. (221 to 230° F.) and kept in a desiccator until required for the breakdown test. Two sheets of the paper were removed at one time from the desiccator and placed between two sheets of tinfoil. This pile-up was then tested at once between brass electrodes with flat polished contact surfaces of the type specified in the Society's Tentative Methods of Testing Sheet and Tape Insulating Materials for Dielectric Strength (D 149 – 27 T).[1]

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part I, p. 995 (1927); also 1929 Book of A.S.T.M. Tentative Standards, p. 577.

These electrodes were cylindrical rods 2 in. in diameter with the edges of the contact surfaces rounded to a radius one-eighth the diameter of the electrodes and arranged to transmit to the pile-up a constant pressure of 15 lb. per sq. in. The condensers were manufactured under as nearly as possible the same conditions and were impregnated with the same material.

Tests were also made on condenser papers conditioned 24 hours at 65 per cent relative humidity and 21° C. (70° F.) immediately prior to testing. The dielectric strength values obtained were in the same relative order as shown for the dried papers. Check tests showed, however, that slight differences in the methods of sampling or of determining the dielectric strength might easily cause greater variations in the dielectric strength results than shown by the lots of paper listed in Table I.

TABLE II.—TEST DATA ON 0.0004-IN. CONDENSER PAPER.

Paper	Porosity of Paper, cc.			Density of Paper as Received	Conducting Paths per Square Foot			Average Breakdown Voltage of 1-mfd. Condensers Using Two Sheets of Paper Between Tinfoils, volts (Alternating Current)
	Maximum	Minimum	Average		Maximum	Minimum	Average	
Lot No. 4T	18.9	6.7	9.7	0.980	7	2	4	655
Lot No. 2T	21.7	5.3	12.8	0.955	5	3	4	680
Lot No. 8D	10.9	0.9	4.4	1.020	8	5	6	945
Lot No. 7T	9.0	4.4	6.0	0.947	8	2	5	954
Lot No. 5T	4.5	1.7	2.6	1.014	5	4	4	1024
Lot No. 3T	4.8	2.7	3.7	0.968	13	4	8	1032
Lot No. 9D	13.4	2.5	6.2	0.980	15	10	12	1060
Lot No. 1D	3.2	1.0	1.9	1.020	17	10	13	1138
Lot No. 12P	3.1	0.7	1.4	1.160	18	11	13	1275
Lot No. 13P	2.8	0.6	0.9	1.180	24	10	16	1340
Lot No. 2D	8.9	1.6	3.6	1.000	10	5	7	1430
Lot No. 1620T	2.9	2.7	2.9	0.956	19	16	17	1603

Comparative dielectric strength tests on condenser papers tend to give, therefore, a slight indication of the comparative dielectric strength of the condensers produced with these papers, but this method of testing is not suitable for routine tests to be used in determining whether the paper is capable of producing condensers of a specified dielectric strength.

RELATION BETWEEN CONDUCTING PATHS IN PAPER AND DIELECTRIC STRENGTH OF CONDENSERS

In considering the other characteristics of condenser papers which may have a bearing on the dielectric strength of the corresponding condensers, it is logical to consider first the number of conducting paths per unit area of the papers. The manufacturers' efforts towards the improvement of their papers have been directed in a large measure towards a reduction in the number of these conducting paths. The number of conducting paths in the condenser papers supplied commercially seldom exceeds 30 per square foot when determined by the Society's Tentative Methods of Testing Untreated Insulating Paper (D 202 - 29 T).[1] Assuming that the average conducting path is effective over an area $\frac{1}{32}$ in. in diameter and that a total of 12 sq. ft. of paper are required in a one-microfarad condenser built with two sheets of paper between metallic foils, the probability that two conducting paths will come in contact when each sheet of paper has 30 conducting paths per square foot is approximately as in the following formula:[2]

$$\frac{\text{Area of Conducting Path in square inches} \times \text{Number of Square Feet of Paired Paper in Condenser} \times \text{Square of Number of Conducting Paths per Square Foot}}{144} =$$

$$\frac{\frac{\pi}{4}\left(\frac{1}{32}\right)^2 \times 6 \times (30)^2}{144} = \frac{4.142}{144} = 2.88 \text{ per cent} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

With 10 conducting paths per square foot, the probability of two conducting paths coming in contact would be only 0.32 per cent, or about 1 in 300.

The assumptions made in deriving this formula are only approximately correct and a portion of the paper required is not within the area between metallic foils. It is further necessary to assume that the conducting paths in the paper remain after impregnation of the condenser units with the usual waxes or impregnating compounds. The formula serves to show, however, that the number of condensers which may be expected to fail at very low voltages, due to conducting paths in the paper, is small if the number of conducting paths per square foot is kept within the usual range.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 758 (1929); also 1929 Book of A.S.T.M. Tentative Standards, p. 602.

[2] This formula may be derived as follows: Let us assume first that the paper has one conducting path per square foot. If we pair two sheets of this paper each 1 sq. ft. in area, the probability that the conducting path in one sheet will meet that in the other is in the ratio of the area of the conducting path to that of the sheet, or $\frac{\frac{\pi}{4}\left(\frac{1}{32}\right)^2}{144}$. If we now have two conducting paths in each one of the sheets 1 sq. ft. in area, there is a like possibility that each path in one sheet may come in contact with either one of the two paths in the other sheet. Likewise, in the case of three conducting paths in each sheet 1 sq. ft. in area, there is a possibility that each path in one sheet may come in contact with either one of the three paths in the other sheet. It is seen that the probability of two conducting paths in the paired sheets coming together increases as the square of the number of conducting paths in each sheet. The probability of conducting paths coming in contact when two sheets, each 1 sq. ft. in area and each having 30 conducting paths, are paired is therefore $\frac{\frac{\pi}{4}\left(\frac{1}{32}\right)^2 \times (30)^2}{144}$. If each sheet is, however, 6 sq. ft. in area instead of 1 sq. ft., the probability of two conducting paths in the paired sheets coming in contact becomes six times greater. The probability of having a path through the two sheets therefore becomes $\frac{\frac{\pi}{4}\left(\frac{1}{32}\right)^2 \times (30)^2 \times 6}{144}$.

The effect of the conducting paths in the papers on the dielectric strength of the corresponding condensers when these paths in the paired sheets do not meet is not so well known. From the data in Table II it is apparent, however, that condensers of high dielectric strength can be produced when using condenser papers in which the number of conducting paths is within the usual range. The lots of paper Nos. 1620T and 2D used in the condensers which showed the best dielectric strength had an average of 17 and 7 conducting paths respectively, while the papers used in the condensers which broke down at low voltages had fewer conducting paths. It would be absurd, however, to conclude that an increase in the number of conducting paths is actually beneficial to the dielectric strength of the condensers, and it is evident that the greater dielectric strength of the condensers made from papers with the higher number of conducting paths is due to these papers being of better quality in some other respects.

TABLE III.—TEST DATA ON 0.0005-IN. CONDENSER PAPER.

Paper	Porosity of Paper, cc.			Average Breakdown Voltage of 1-mfd. Condensers Using Two Sheets of Paper Between Tinfoils, volts (Alternating Current)
	Maximum	Minimum	Average	
Lot No. S_1	25.2	4.8	14.1	712
Lot No. D_1	22.0	2.9	11.6	747
Lot No. D_2	9.6	1.2	4.8	955
Lot No. S_2	6.4	1.6	3.1	1280
Lot No D_3	2.4	0.7	1.5	1418
Lot No. S_3	3.8	1.5	2.3	1671
Lot No. H_1	0.8	0.4	0.5	1679
Lot No. H_2	0.6	0.2	0.4	1712

RELATION BETWEEN DENSITY OF PAPER AND DIELECTRIC STRENGTH OF CONDENSERS

Practically all condenser paper specifications contain a requirement covering the minimum apparent density of the paper. That variations in the average apparent density of the paper have no important effect on the dielectric strength of the corresponding condensers is indicated by the data in Table II. Condensers with average breakdown voltages of 680 and 1603 were produced from lots Nos. 2T and 1620T, respectively, which have approximately the same apparent density. The paper of lot No. 1620T, from which the condensers of highest dielectric strength were produced, was among the lowest in average apparent density and had the highest area per pound of any of the lots listed in Table II.

The above findings are contrary to the usual understanding and to some published data[1] on other insulating papers, as to the effect of the density on the dielectric strength of the paper. Changes in density, as well as in some other characteristics of the paper, such as the degree of hydration, undoubtedly affect the degree of penetration of the waxes and other impregnating materials, and it is probable that high density of the paper tends to prevent thorough drying and complete impregnation of the condensers. It is therefore possible

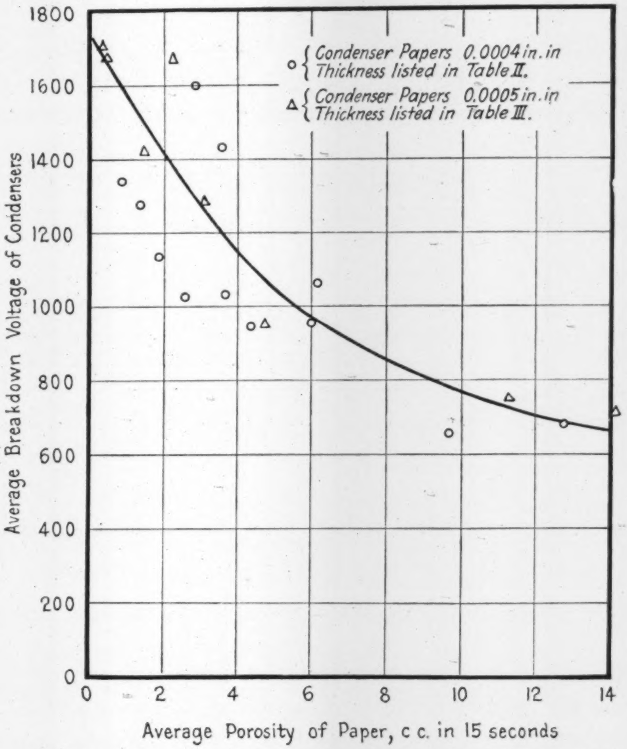

FIG. 1.—Relation of Porosity of Condenser Paper to Breakdown Voltage of Condensers Using 2 Sheets of Paper Between Metallic Foils.

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[1] T. N. Riley and T. R. Scott. "Electrical Insulating Papers for the Manufacture of Power Cables," *Journal*, Inst. Electrical Engrs., Vol. 67, p. 946 (1929).

that an increase in the density of the paper would be detrimental rather than beneficial under the usual condenser manufacturing conditions, even though an increase in the density were found to be of advantage when unimpregnated or thoroughly impregnated papers are used.

RELATION BETWEEN POROSITY OF PAPER AND DIELECTRIC STRENGTH OF CONDENSERS

The relation between the porosity of the paper and the dielectric strength of the corresponding condensers is indicated to some extent in Table II and is shown more clearly in Table III and in Fig. 1.

TABLE IV.—POROSITY TESTS OF UNIFORM AND NON-UNIFORM CONDENSER PAPERS.

0.0004-in. Condenser Paper, Uniform in Porosity—Lot No. 1620-T					0.0005-in. Condenser Paper, Non-Uniform in Porosity—Lot No. 889-S				
Porosity, cc. (15 Samples)	Ultimate Dielectric Strength of Corresponding Condensers, volts (alternating current) (50 Units)				Porosity, cc. (15 Samples)	Ultimate Dielectric Strength of Corresponding Condensers, volts (alternating current) (50 Units)			
2.7	1320	1750	1950	2100	4.5	700	250	800	1330
2.7	1400	1740	1050	1950	3.9	1240	830	1750	1450
2.9	2020	1460	1280	1520	5.1	510	1240	640	1440
2.9	2400	1380	1040	1540	5.5	690	1080	800	610
2.9	1460	1660	2160	1550	4.2	660	1350	1190	710
2.9	1640	1760	1800	1150	5.0	520	580	1120	850
2.9	1800	1750	1500	1190	16.0	660	1070	810	1440
2.9	1150	1320	1250	1920	15.4	660	400	1330	250
2.9	1020	1750	1940	1460	18.4	550	560	480	420
2.9	1220	1950	1860	1440	16.2	860	1220	720	1240
2.7	1850	1580	1720	1960	14.9	650	1720	1220	970
2.9	1380	2120	2000		14.9	700	1230	700	
2.9	1480	1400	1440		3.9	1170	580	500	
2.9					4.1				
2.9					4.0				
Average.......2.9	Average.................1603				Average... 9.1	Average 889			
Maximum.....2.9					Maximum. 18.4				
Minimum.....2.7					Minimum.. 3.9				

In general, the data indicate that the condensers are of low dielectric strength when the paper used is of high porosity and that the condensers are of high dielectric strength when the paper used is of low porosity. Figure 1 shows the approximate average relation between the porosity of the paper and the breakdown voltage of the condensers under the conditions of manufacture encountered. Variations in the process of manufacturing the condensers probably account in a large measure for the apparent discrepancies in the breakdown voltages of condensers made with papers of approximately the same porosity, and it is to be expected that the dielectric strength of the condensers produced under the usual manufacturing conditions is somewhat less in all cases than the dielectric strength of the condensers produced under ideal conditions of manufacture.

Although several million condensers have been produced since the investigation described was made and papers from several domestic and foreign sources have been used, there has been no instance in which condensers of high dielectric strength could not be produced with papers of uniform low porosity or in which condensers of high dielectric strength were produced with papers of high porosity. During this period some condensers of low dielectric strength were obtained, but in all cases it was found possible on rechecks to produce condensers having dielectric strengths reasonably close to those which might be expected from a consideration of the porosity of the paper. The condensers referred to were all wound with two sheets of paper between sheets of tinfoil and the papers ranged in apparent density from 0.9 to 1.2 and in conducting paths per square foot from 2 to 25.

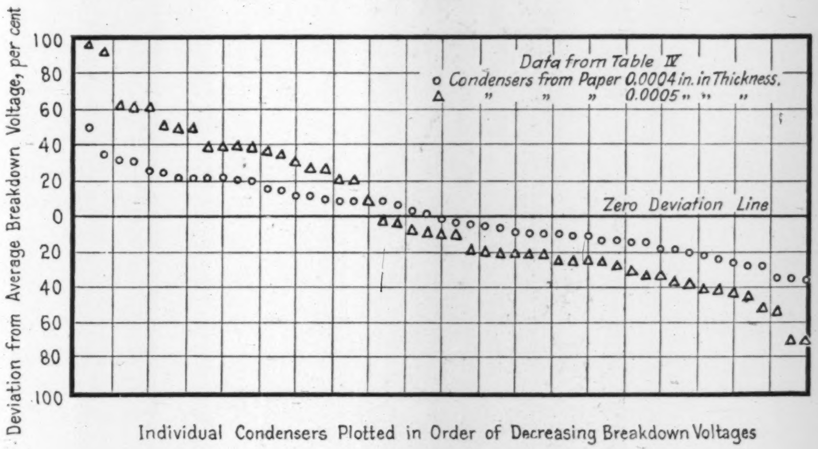

FIG. 2.—Percentage Deviation of the Breakdown Voltage of the Individual Condensers from the Average Breakdown Voltage of the Corresponding Lot.

Reasonable uniformity of the paper from a porosity standpoint as well as low average porosity are desirable if condensers of high dielectric strength are to be produced. Non-uniformity of porosity corresponds to non-uniformity in formation of the paper sheet. With the paper showing only a small percentage of its area as high porosity spots there is little danger of two such spots coming in contact when the paper is paired. If the percentage of the area of the paper which is of high porosity is large, a considerable proportion of the condensers break down at low voltages. This is illustrated by the data in Table IV. The 0.0004-in. paper (lot 1620T) is of low porosity and exceptional uniformity. The 0.0005-in. paper (lot No. 889-S) paper is non-uniform in porosity. Correspondingly, the condensers made with the first paper are all of high dielectric strength and the breakdown voltage of the best unit from this lot is less than $2\frac{1}{2}$ times the breakdown voltage of the poorest unit. The condensers made with the second paper range from very poor to very good in dielectric strength,

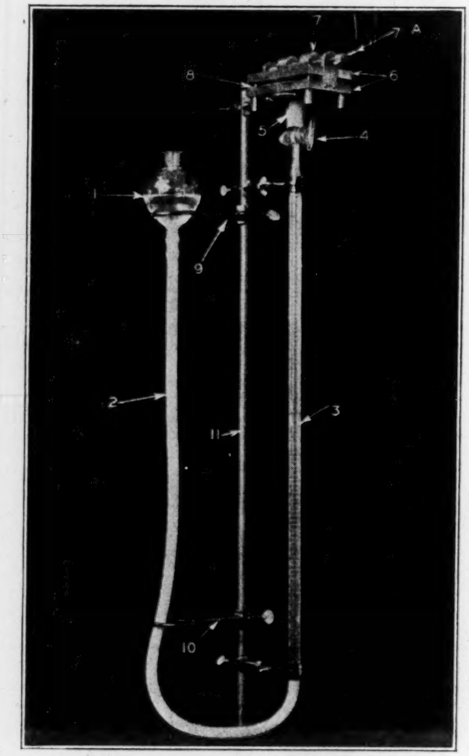

FIG. 3.—Porosity Apparatus.

1, a 250-cc. pear shaped aspirator bottle.
2, soft rubber tubing 33 in. long, bore $\frac{3}{8}$ in.
3, a 100-cc. burette, length 21.5 cc. from the 0-cc. to the 88.7-cc. calibration, graduated in 0.1 cc.
4, a glass stop-cock ground in burette to give air-tight joint.
5, pressure tubing 2 in. long, bore 0.20 in., used to connect burette to nipple protruding from the lower clamping plate.
6, clamping plates. Upper plate has a hole 1 in. in diameter through center. Lower plate has a corresponding hole or 1 in. in diameter cut to a depth of $\frac{1}{8}$ in. The nipple referred to under 5 has a $\frac{1}{4}$-in. internal diameter and fits flush at the bottom and in center of the 1-in. hole in lower plate.
7, clamp eccentric to tighten clamping plates, operated by wing handle *7A*.
8, two $\frac{1}{32}$-in. pure gum rubber sheets having holes 1 in. in diameter cut through center to correspond to holes in clamping plates. One sheet is $2\frac{3}{4}$ by $2\frac{3}{4}$ in. and is cemented to the upper plate. The other sheet is 3 by 3 in. and is cemented to the lower plate.
9 and *10*, ring holders, slotted to permit easy removal of aspirator bottle.
11, steel rod to which apparatus is attached.

and the breakdown voltage of the best unit is 7 times the breakdown voltage of the poorest unit.

Figure 2 shows the percentage deviation of the breakdown voltage of each individual condenser from the average breakdown voltage of the corresponding lot. The condensers made from the 0.0004-in. paper of uniform porosity are grouped much more closely along the zero deviation line than the condensers made from the 0.0005-in. paper of non-uniform porosity. This close grouping to the zero deviation line is an important characteristic when condensers are to be used at voltages close to their rated value, for it is evident that of two lots of condensers having the same average breakdown voltage, the one with the closest grouping may be expected to show the smallest number of failures.

A review of the data so far presented also indicates that an increase in the thickness of the paper does not result in any marked improvement in the dielectric strength of the corresponding condensers unless the thicker paper is of lower porosity. Although it would appear less difficult to produce paper of low porosity when its thickness is increased, the 0.0005-in. papers examined have not been appreciably better than the 0.0004-in. papers from a porosity standpoint and, in general, the condensers made from papers 0.0004 in. in thickness have shown approximately the same average dielectric strength as the condensers made from papers 0.0005 in. in thickness.

POROSITY APPARATUS AND METHOD OF DETERMINING POROSITY

The apparatus used in the porosity tests is shown in Fig. 3. It is a modification of an apparatus designed by the Westinghouse Electric and Manufacturing Co. several years ago. One advantage of this apparatus over other types available is that with the exception of the clamping device it can be assembled from parts which can be readily obtained from laboratory supply concerns. The clamping device is also simple and can be easily constructed. Such adjustments as may be necessary are made in the connections to maintain the volume of the air space from the 0-cc. reading of the burette to the paper in the clamp at approximately 11 cc.

With the apparatus set up as shown in Fig. 3, the stop-cock, *4*, is opened, approximately 250 cc. of water are poured into the aspirator bottle, *1*, and the height of the bottle is adjusted to give a burette, *3*, reading of 0 cc. with the water in the burette and in the aspirator bottle on the same level. One of the holders, *9*, is fixed to hold the aspirator bottle in this position. The aspirator bottle is then removed from this holder and, with the stop-cock still open, it is lowered until the burette shows a reading of 88.7 cc. with the water in the burette and in the aspirator bottle on the same level. The ring holder, *10*, is fixed so as to hold the aspirator bottle in this position. The apparatus is now ready for operation.

With the aspirator bottle in the upper position and the water in the burette reading 0 cc., the paper to be tested is inserted between the jaws of the clamps, *8*, and the wing lever *7A* is tightened. The stop-cock is closed and the aspirator bottle is placed in the lower holder. The stop-cock is then opened for 15 seconds. With the stop-cock closed, the aspirator bottle is raised until the water in the bottle and in the burette are on the same level and a reading of the number of cubic centimeters of air which have been drawn through the paper is taken.

Routine tests are usually made on paper held under ordinary room conditions, but for close checks conditioning of the paper for 24 hours at 65 per cent relative humidity and 70° F. immediately prior to testing is considered necessary.

In the inspection of large lots of condenser paper of reasonably uniform quality, three samples from each of five rolls selected from each 2000 lb. in the shipment are considered sufficient in checking the porosity of the paper. In checking new products or non-uniform paper, the above number of samples from each case of 200 to 400 lb. is considered desirable.

CONTROL OF POROSITY OF CONDENSER PAPER

Although various methods of checking the porosity of condenser papers have been in use and some specifications contain requirements on porosity, it seems evident that the relation between the porosity of the paper and the dielectric strength of the corresponding condensers has not been generally understood and that in many cases the paper manufacturers have not been aware of the possibility of improving the quality of the paper by decreasing its porosity. The data obtained in the investigation described have been discussed freely with paper manufacturers and in some instances it has been found possible to obtain marked improvements in the porosity of the paper and in the dielectric strength of the corresponding condensers.

The porosity limits which the paper should meet to produce condensers of satisfactory dielectric strength depends of course on the service conditions. Practically all wound condensers in which two sheets of paper are used between metallic foils are intended for service at low voltages. For condensers of this type reasonably uniform paper with a maximum average porosity of 6 cc. by the method given is expected to produce condensers of adequate dielectric strength. A material of higher porosity can probably be used satisfactorily if the condensers are to be used at very low voltages. However, there appear to be very few instances in which high-porosity paper can be used to advantage.

The desirability of obtaining a paper of uniform porosity has already been mentioned. Control of the maximum porosity and of the average porosity of the paper is therefore advisable. If allowance is made for occasional spots of high porosity which are sometimes found in papers of reasonably good quality, a requirement of "not more than one reading in 15 to be greater than 8.0 cc." appears adequate to cover the maximum allowable variations in porosity of paper with a specified maximum average porosity of 6.0 cc.

For condensers which are used at high voltages, selected papers of lower porosity can often be used to advantage. Requirements of "average porosity not more than 3.0 cc. in 15 seconds and not more than one single reading in 15 to be greater than 5.0 cc." are considered adequate for this grade of paper. From a quality standpoint there appears to be no appreciable advantage in more stringent porosity requirements and at the present time stricter requirements could not be met generally by paper manufacturers.

CONCLUSION

A review of the investigations described indicates that variations in the density of condenser paper have no noticeable effect on the dielectric strength of the corresponding condensers. Minimum apparent density requirements on condenser papers are therefore considered to be unnecessary.

When in small numbers, conducting paths through the paper have no important effect on the dielectric strength of condensers wound with two sheets of paper between tinfoils. Conducting paths in the paper result in "shorts" (or in very low dielectric strength) in a portion of the corresponding condensers, but the percentage of the condensers failing in this manner may be expected to be negligible when the number of conducting paths is small. However, inasmuch as the percentage of probable condenser failures due to conducting paths through the paper increases approximately as the square of the number of conducting paths per unit area, it is considered desirable that the number of conducting paths be small.

The variations in the porosity of the paper have been found to have an important bearing on the dielectric strength of the corresponding condensers. Reasonable uniformity in porosity and low porosity have been shown to be of advantage in most cases. Maximum porosity requirements for papers for low-voltage condensers and for papers for high-voltage condensers have been suggested. The paper manufacturer's ability to produce low-porosity condenser paper has been considered together with the condenser manufacturer's desire for high-grade papers and the requirements proposed give limits on porosity of condenser papers which can be enforced to advantage under present manufacturing conditions.

Acknowledgment.—Credit is due Messrs. K. M. Huston and P. B. Brice of the Western Electric Co. for much tedious experimental and control work undertaken during the investigations described. The cooperation of C. H. Dexter and Sons, the Smith Paper Co., the Schoeller-Hoesch-Schmidt Corp., the Standard Products Corp., and Fred C. Strype in furnishing samples, trial lots of condenser paper and manufacturing information, is gratefully acknowledged.

THERMAL TRANSMISSION OF FABRICS

By Ephraim Freedman[1]

Synopsis

Tests of heat transmission through porous materials such as cotton and wool fabrics were conducted in moving air by using a calorimeter containing an electric heater and surrounded by the material under test, the material being exposed to temperatures down to 20°F. and wind velocities up to 25 miles per hour. The electrical input to the heater was measured in the usual way when the temperature difference, as indicated by specially-constructed xylene liquid thermometers, became constant. The specimens under test had an area of approximately 100 sq. in.

The energy input for temperature differences of 70°F. was found to vary from 15 watts for good blanket materials to 135 watts for gauze fabrics, the input depending on texture and wind velocity. The method of test is sensitive and the results reproducible.

Introduction

Interest has often been expressed in the thermal insulation afforded by textile fabrics against the temperatures and wind velocities encountered during wintry weather. Specifically, the question is raised as to the superiority of one fabric over another for use as a blanket or as an outer or under garment. Looking over the literature on heat transmission through insulating materials, it was found that most methods of test were concerned with the temperature range suitable for steam pipe coverings and furnaces, or else suitable for refrigerating machines. Relatively little attention has been paid to thermal transmission over the range from 20 to 100°F. with air circulating past the material under test.

Various methods for testing the thermal insulation of fabrics have been tried. In one method, use is made of a Dewar jar filled with a refrigerant. The test specimen is clamped across the top of the jar and the time is observed for the temperature of the contents to be raised to that of the room. In another method a stream of heated water is caused to circulate through an inflated rubber bladder insulated with the material under test, the entire unit being suspended in a cold chamber. Temperature readings of the water entering and leaving the bladder, together with the rate at which it circulates through the unit, gives the amount of heat transmitted through the fabric. None of the methods previously advanced were considered sufficient for the testing of fabrics for one or more of the following reasons: (1) the temperatures of the surfaces were not maintained constant, (2) the temperatures at the surfaces of the specimen were not definitely measured, and (3) the conditions of test did not approximate those under which textiles are normally used.

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[1] Director, Macy Bureau of Standards, R. H. Macy and Co., Inc., New York City.

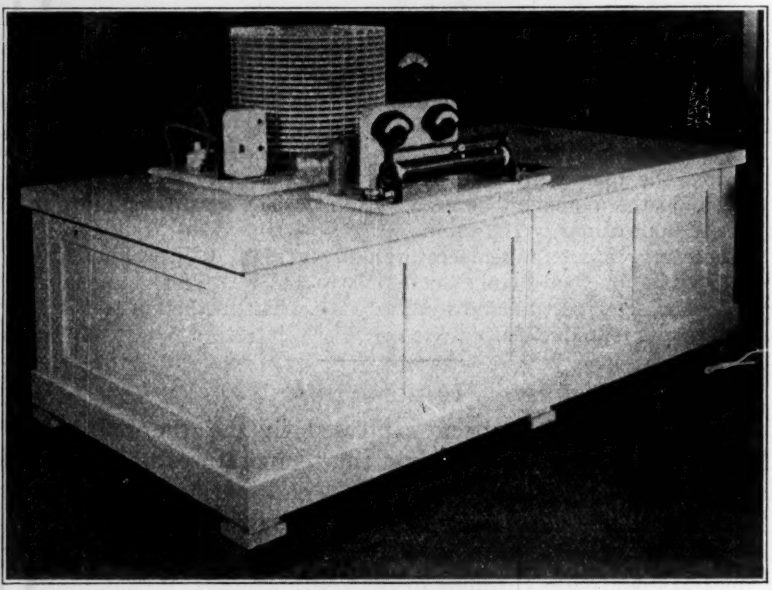

FIG. 1.—Thermal Transmission Apparatus.

Consideration of average wind velocities and of typical temperatures during the winter months led to the decision to design an apparatus for an air speed of 25 miles per hour and a temperature as low as 20°F. The appearance of the apparatus is shown in Figs. 1 and 2, and the plan and elevation are shown in Fig. 3. The cooled air passes around the specimen under test wrapped around a calorimeter, while heat of appropriate amount is developed within the calorimeter to maintain its temperature at some predetermined value.

APPARATUS

The calorimeter, *c*, Fig. 3, around which is wound the specimen, *S*, under test, is of novel construction. It is a cylindrical container measuring 10 in. in height and 3 in. in outside diameter, and the wall encases the bulb of a xylene thermometer. This bulb is made of bronze tubing 0.090 in. in outside diameter and 400 in. long wound helically on a cylinder of $\frac{1}{32}$-in. sheet copper. The spaces between convolutions are filled with lead so as to form a smooth outside surface. This gives a thermometric element with a total conducting surface of nearly 100 sq. in. The indicating instrument for this thermometer has a range from 90 to 110°F. with scale divisions of $\frac{1}{4}$°F., and is equipped with electric contacts for controlling the temperature within a narrow range. The thermometer was constructed for bulb immersion only and was compensated for atmospheric fluctuations along the line and at the instrument.

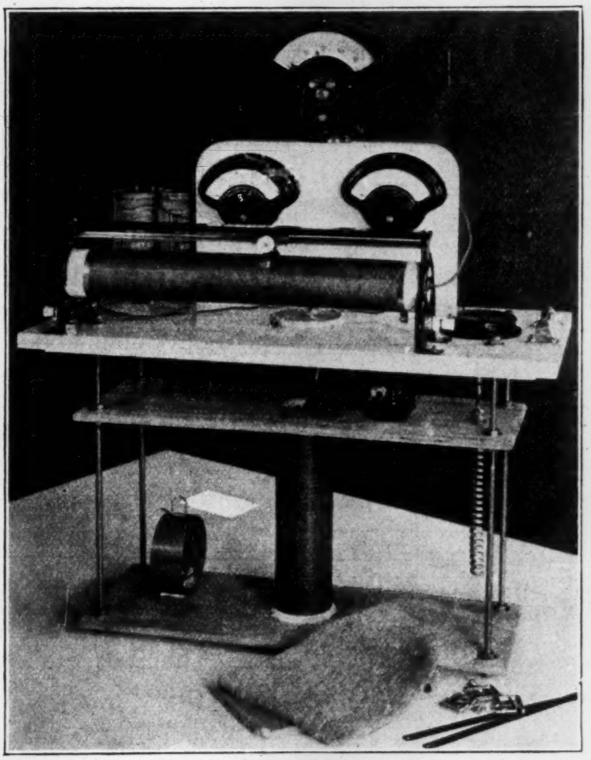

FIG. 2.—Platform with Calorimeter, Thermometer, Anemometer, Recording Instruments, and Rheostat.

The thermometer system is filled completely with xylene, the bulb being a capillary tube 0.008 in. in diameter. Increase of temperature causes the pressure to rise, thus activating a coiled Bourdon spring in the instrument which, in unwinding, causes a pointer to move across the scale.

The duct, *D*, for circulating air past the calorimeter is made of copper and has an average length of 12 ft. and an aggregate volume of 12 cu. ft. The same air is circulated through the duct by a blower, *B*, driven by a 1 h-p. electric motor, *M*, the speed being controlled by a rheostat. This duct is embedded in cork within a portable table 85 in. long, 44½ in. wide and 32 in. high. Mounted on this table is a General Electric Type DR-4 refrigerating unit, *R*, with its cooling fins, *F*, projecting into the duct. Another aperture in the duct permits the insertion of the calorimeter, together with a thermometer,

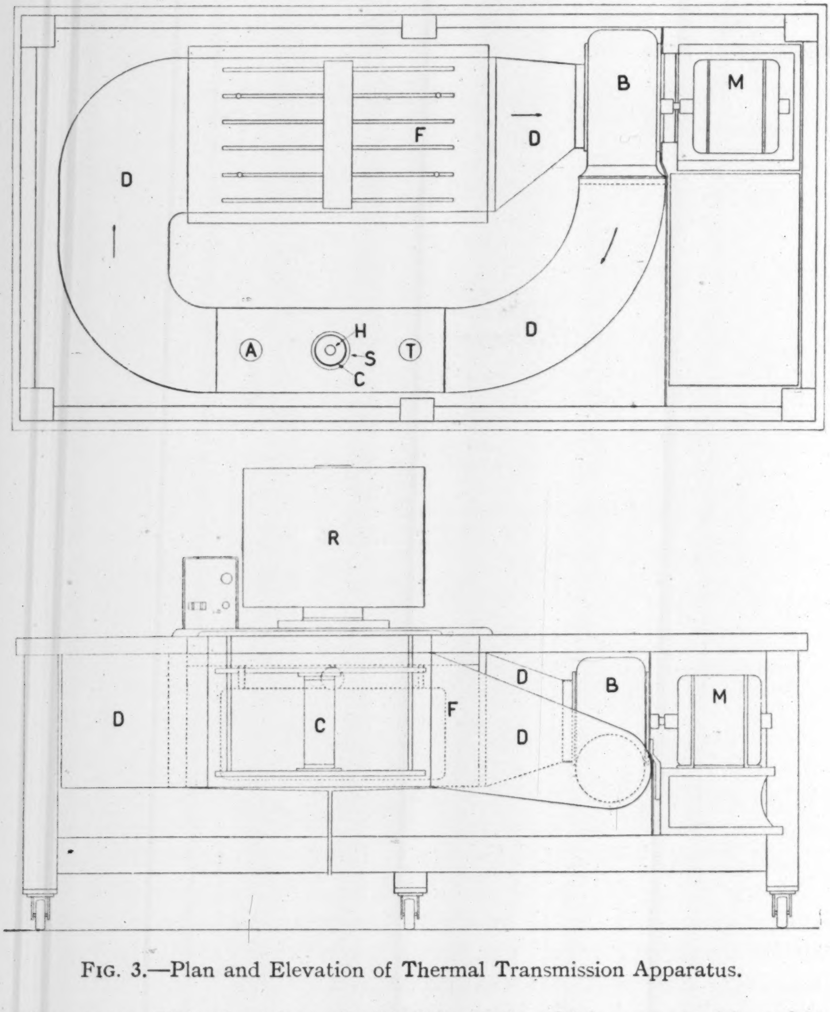

Fig. 3.—Plan and Elevation of Thermal Transmission Apparatus.

T, and anemometer, *A*. These devices are mounted on the underside of a platform (see Fig. 2) which covers the aperture. The calorimeter is insulated top and bottom with $\frac{3}{8}$-in. asbestos fiber board.

A heater, *H*, of nichrome wire wound through mica is placed within the calorimeter, and leads are brought through the cover to the necessary electrical measuring apparatus and control equipment mounted above the table. The heater is connected to the 115-volt direct-current supply circuit, through a rheostat, ammeter and the relay contacts, and a voltmeter is connected directly across the heater. Should the temperature of the calorimeter rise beyond some predetermined point, contact will be established for battery current through the coils of the relay to open the heater circuit.

TABLE I.—MATERIALS SUBJECTED TO TEST.

Specimen	Description	Composition	Count		Weight, oz. per sq. yd. Under Prevailing Conditions	Thickness, in.
			Ends	Picks		
No. 1	Blanket material, broken twill weave, napped surface	Wool	28	25	8.24	0.215
No. 2	Blanket material, broken twill weave, napped surface, washed	Wool	28	26	8.67	0.179
No. 3	Blanket material, broken twill weave, napped surface	Wool	24	22	8.58	0.274
No. 4	Blanket material, broken twill weave, napped surface, washed	Wool	28	22	9.44	0.232
No. 5	Blanket material, twill weave, napped filling	Cotton	37	26	7.24	0.204
No. 6	Blanket material, twill weave, napped filling	Cotton, 96.6 per cent; wool, 3.4 per cent	35	28	7.22	0.168
No. 7	Blanket material, wool-faced, cotton ground	Wool, 65.8 per cent; cotton, 34.2 per cent	22	19	12.8	0.245
No. 8	Duck, plain weave	Cotton	34	29	6.4	0.049
			Wales	Courses		
No. 9	Overcoating, brushed knit	Wool	13	16	19.65	0.256
No. 10	Overcoating, curl-faced	Wool	16	22	20.86	0.360
No. 11	Overcoating, pile knit	Cotton, 39.6 per cent; wool, camel-hair and llama, 60.4 per cent	Wales 17	Courses 17	15.97	0.279
No. 12	Lining, coat, twill weave	Cotton	54	51	5.96	0.065
No. 13	Lining, coat, outing flannel	Cotton	50	53	6.25	0.097
No. 14	Overcoating, pile fabric	Wool	..	..	15.5	0.444
No. 15	Gauze	Cotton	27	26	0.842	0.010
No. 16	Alaska seal	Fur	..	..	21.4	0.360

The component parts of the apparatus were calibrated and trial runs were made to determine the reproducibility of results.

MATERIALS

Specimens of wool, cotton and wool, and cotton materials (see Table I) of various constructions, weights and thicknesses, and a specimen of Alaska seal peltry were subjected to test of thermal transmission.

The material enumerated was chosen so as to give a picture of its behavior under test. The determinations of composition, count and weight were conducted as prescribed in the standard methods of the Society. The thickness of the various materials was determined by an optical method.

TEST METHODS AND DATA

A test in the thermal transmission apparatus is conducted substantially as follows: The duct is cooled to the desired temperature by means of the refrigerating unit. A specimen is wrapped closely but without tension around the calorimeter, its ends are drawn between two thin strips (hack saw blades were found satisfactory) so that only one layer of the specimen is in contact with the cylinder, and the strips are secured by clamps. The blower is set in motion. Current is supplied to the heater and the voltage across it is adjusted by a slide wire resistance until a constant temperature, approximately 98.6°F., is established. This adjustment requires approximately one-half hour. At least three readings are then taken at ten-minute

TABLE II.—FOUR READINGS TAKEN AT TEN-MINUTE INTERVALS.

Specimen	Temperature, deg. Fahr.			Volts	Amperes	Watts	
	Calorimeter	Duct	Difference			Total	Per 1° F.
No. 10........	98.1	38.0	60.1	21.3	1.2	25.6	0.426
	98.3	38.5	59.8	21.3	1.2	25.6	0.428
	99.0	39.0	60.0	21.3	1.2	25.6	0.427
	99.2	39.5	59.7	21.2	1.2	25.4	0.426

TABLE III.—WATTS REQUIRED FOR TEMPERATURE MAINTENANCE OF VARIOUS FABRICS.

Specimen	Average Readings with Nominally Still Air				Average Readings with Wind Velocity at 14.2 miles per hour			
	Temperature, deg. Fahr.		Watts		Temperature, deg. Fahr.		Watts	
	Calorimeter	Duct	Total	Per 1° F. Difference	Calorimeter	Duct	Total	Per 1° F. Difference
No. 1.	96.7	41.4	17.2	0.311	99.3	35.8	38.9	0.613
No. 2..........	99.2	37.3	20.9	0.337	98.1	35.1	37.9	0.601
No. 3..........	97.9	39.5	17.7	0.303	97.9	28.6	38.8	0.560
No. 4..........	....	....	....	.....	99.4	39.5	32.6	0.544
No. 5..........	97.9	46.7	16.9	0.329	97.8	40.3	31.4	0.546
No. 6..........	97.1	46.8	17.5	0.347	96.5	40.5	33.9	0.606
No. 7..........	98.2	43.4	16.7	0.306	99.2	39.2	27.5	0.458
No. 8..........	95.9	43.0	27.8	0.526	99.2	42.3	25.0	1.67
No. 9..........	96.7	39.8	18.1	0.319	98.1	36.2	29.5	0.476
No. 10.........	97.5	44.4	14.5	0.272	98.7	38.8	25.6	0.427
No. 11.........	97.9	38.0	18.0	0.301	98.3	24.6	32.8	0.515
No. 12.........	....	....	....	.....	99.7	34.9	88.0	1.36
No. 13.........	....	....	....	.....	100.6	35.7	67.9	1.05
No. 14.........	99.4	40.0	14.4	0.242	98.5	31.7	39.6	0.593
No. 15.........	99.4	42.5	27.5	0.483	100.6	35.6	132.5	2.04
No. 16.........	100.8	35.2	14.6	0.222	99.0	31.3	24.2	0.357

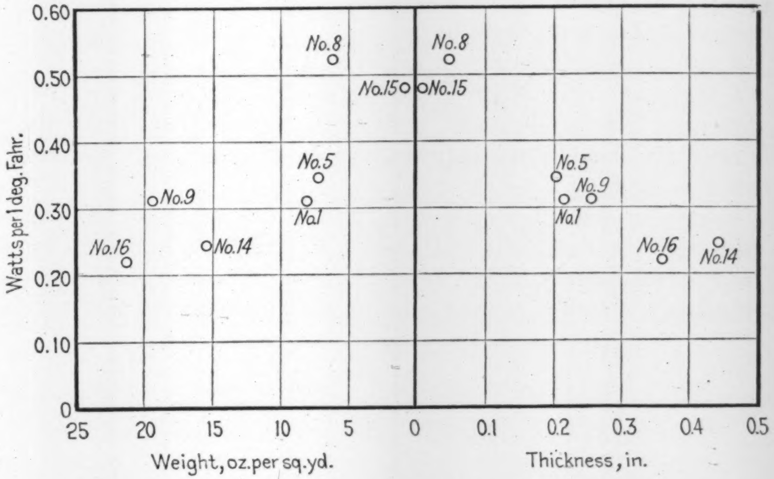

FIG. 4.—Thermal Transmission of Fabrics in Nominally Still Air.

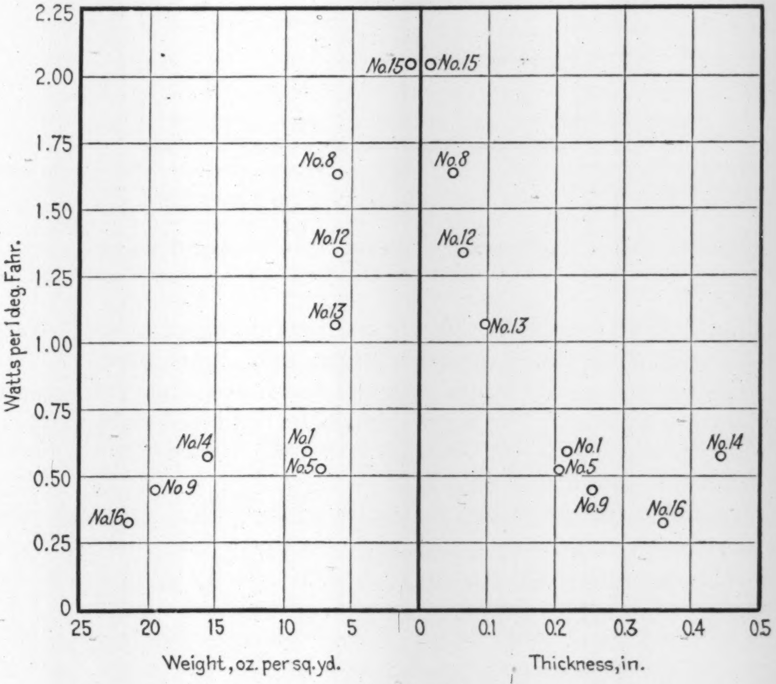

FIG. 5.—Thermal Transmission of Fabrics with Wind Velocity at 14.2 Miles per Hour.

intervals. The number of watts consumed is calculated from the voltmeter and ammeter readings.

A typical set of readings is given in Table II.

A measure of the thermal transmission of the specimen in terms of watts per 1°F. is obtained by dividing the electrical input by the difference in temperature between the calorimeter wall and the air within the duct.

A series of check tests disclosed that it was necessary to maintain an electrical input of 2.325 watts per 1°F. difference in order that the elevated temperature of the bare calorimeter wall remain constant when subjected to low temperature and a wind velocity of 14.2 miles per hour. With nominally still air an electrical input of 0.427 watts per 1°F. difference was recorded with the calorimeter bare.

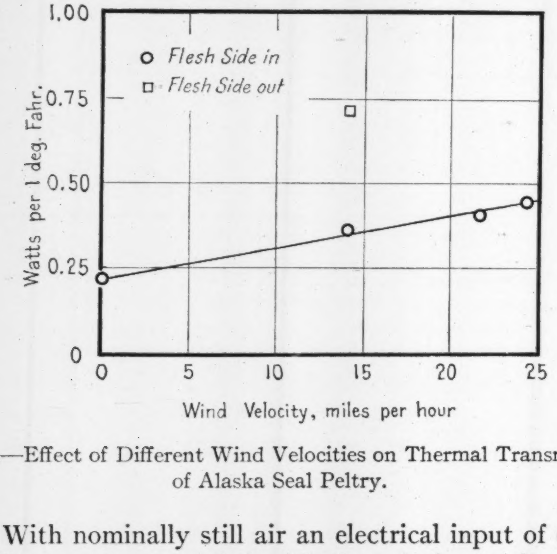

FIG. 6.—Effect of Different Wind Velocities on Thermal Transmission of Alaska Seal Peltry.

The watts required by the different specimens when subjected to temperature differences between calorimeter wall and duct of about 60°F., with nominally still air, and with wind velocity at 14.2 miles per hour, are shown in Table III.

A number of test results were plotted (see Figs. 4 and 5) so as to show the effect of weight and thickness upon their thermal transmission in nominally still air and with wind velocity at 14.2 miles per hour.

Figure 6 illustrates the effect of wind velocities ranging from zero to 24.3 miles per hour on a specimen of Alaska seal peltry. It also discloses the difference in thermal transmission of this peltry with the flesh side turned toward and away from the calorimeter.

The results of the different specimens tested with wind velocity at 14.2 miles per hour disclosed a range in electrical input from 0.357 to 2.04 watts per 1°F. With nominally still air a range of 0.222 to 0.526 watts per 1°F. was noted. A decrease in heat transmission was noted after specimens Nos. 1 and 3 were washed (see specimens Nos. 2 and 4). With nominally still air, specimens Nos. 8 and 15 required greater electrical input than did the bare calorimeter. While the readings taken with nominally still air may not be as reliable as those taken with wind velocities because of inability to control the convection currents, the method of test approximates conditions often encountered in confined spaces, such as vaults, cold storage chambers, or non-ventilated rooms.

TABLE IV.—THERMAL CONDUCTIVITY OF TEXTILE FABRICS.

(Expressed in British thermal units per square foot per hour per 1°F.)

Specimen	Description	In Nominally Still Air	With Wind Velocity at 14.2 miles per hour
No. 1	Blanket material, broken twill weave, napped surface	1.617	3.188
No. 2	Blanket material, broken twill weave, napped surface, washed	1.752	3.125
No. 3	Blanket material, broken twill weave, napped surface	1.576	2.912
No. 4	Blanket material, broken twill weave, napped surface, washed	.....	2.829
No. 5	Blanket material, twill weave, napped filling	1.711	2.839
No. 6	Blanket material, twill weave, napped filling	1.804	3.151
No. 7	Blanket material, wool-faced, cotton ground	1.591	2.381
No 8	Duck, plain weave	2.735	8.684
No. 9	Overcoating, brushed knit	1.659	2.475
No. 10	Overcoating, curl-faced	1.414	2.220
No. 11	Overcoating, pile knit	1.565	2.678
No. 12	Lining, coat, twill weave	.....	7.072
No. 13	Lining, coat, outing flannel	.....	5.460
No. 14	Overcoating, pile fabric	1.258	3.084
No. 15	Gauze	2.512	10.608
No. 16	Alaska seal	1.154	1.856

TABLE V.—INSULATION FACTOR OF TEXTILE FABRICS BASED ON ELECTRICAL INPUT PER 1°F.

Specimen	Wind Velocity, 14.2 miles per hour		Specimen	Wind Velocity, 14.2 miles per hour	
	Watts per 1° F.	Insulation Factor		Watts per 1° F.	Insulation Factor
1	0.613	3.79	10	0.427	5.45
2	0.601	3.87	11	0.515	4.52
3	0.560	4.15	12	1.36	1.71
4	0.544	4.27	13	1.05	2.21
5	0.546	4.26	14	0.593	3.92
6	0.606	3.84	15	2.04	1.14
7	0.458	5.08	16	0.357	6.57
8	1.67	1.39	16	0.725	3.21
9	0.476	4.88	Bare Calorimeter	2.325	1.00

The results show the suitability of the apparatus for the testing of fabrics, and demonstrate the duplication of data obtained with it.

While the results are expressed in terms of watts per 1°F., they may also be converted to B. t. u.'s per square foot per hour per 1°F. as shown in Table IV.

The results may also be expressed in a relative manner which may prove of more practical value in so far as enabling one to grade textile fabrics as they are without reference to thickness and weight. In order to do so one must look upon the bare calorimeter wall as furnishing no degree of protection. When supplied with 0.427 watts in nominally still air, or with 2.325 watts with a wind velocity of 14.2 miles per hour, it may be said to have an insulation factor of unity. Then specimen No. 1, with a wattage of 0.311 would have an insulation factor of 0.427 divided by 0.311 = 1.37 in nominally still air, and a factor of 2.325 divided by 0.613 = 3.79 in air moving at 14.2 miles per hour. To obtain a relative measure of thermal insulation, and recognizing the danger of placing too much dependence upon temperature readings in nominally still air, the figures with wind velocity (14.2 miles per hour) are used to give the insulation factors shown in Table V.

CONCLUSIONS

The thermal transmission apparatus permits of the rapid and accurate measurements of thermal transmission of textile fabrics under conditions similar to actual use.

The results are capable of duplication, their accuracy being estimated to be between 1 and 2 per cent.

The method appears to be sufficiently reliable to warrant further tests (1) of the thermal transmission of textile fabrics with the interposition of an air cushion between the fabric and the calorimeter wall and (2) of the rate of evaporation of moisture under conditions similar to actual use.

Because of the design of the calorimeter, the apparatus may prove of value in determining the thermal transmission of pipe coverings.

Acknowledgment.—Grateful acknowledgment is made of the valuable assistance of Erich Hausmann and his associates of the Brooklyn Polytechnic Institute in the design of the apparatus, and to the Boyce Moto-Meter Co. for the construction of the calorimeter and thermometer.

DISCUSSION

Mr. H. E. Schiefer[1] (*presented in written form*).—The thermal transmission of fabrics is one of the important "consumer properties." Mr. Freedman's apparatus is a compact, self-contained unit for measuring the relative thermal transmission of fabrics in moving air. It can be set up almost anywhere that electric current is available and accordingly it will be of general interest.

Mr. Freedman states, "None of the methods previously advanced were considered sufficient for the testing of fabrics for one or more of the following reasons: (1) the temperatures of the surfaces were not maintained constant, (2) the temperatures at the surfaces of the specimen were not definitely measured, and (3) the conditions of test did not approximate those under which textiles are normally used." It is, then, fair to compare the new method with the old in these respects.

The record in Table II of Mr. Freedman's paper shows that the temperature of his calorimeter increased from 98.1 to 99.2° F., that is, 1.1° F. in 30 minutes during a typical test. Evidently a quantity of energy was being stored up in the calorimeter. The amount would depend on the increase in temperature, the specific heat and mass of the calorimeter. It is quite possible that in another run the heat supplied might be less than that transferred and a loss from the calorimeter would take place. The surface in contact with the fabric in some of the previous methods was maintained at a more constant temperature than that reported in this paper.

Mr. Freedman's second objection to previous methods is that the temperature at the surfaces of the specimen were not definitely measured. Neither were they measured in the experiments reported in this paper. The surface temperature of a fabric especially that of a napped fabric is indefinite. In the present method the temperature of the air stream is measured 7 to 9 in. from the surface of the specimen before the air reaches it. Mr. Freedman does not report the temperature of the air in other directions from the specimen yet it is reasonable to suppose that the temperature is not the same all around as Mr. Freedman assumes. The values for thermal transmission obtained with this method are therefore not absolute values, they are only relative.

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[1] Associate Physicist, U. S. Bureau of Standards, Washington, D. C.

The third objection to previous methods is that the conditions of test do not approximate those under which textiles are normally used. Textiles are used under so widely different conditions that it is difficult to construct an apparatus that will approximate all conditions. For example, the thermal transmission depends upon the nature of the hot surface in contact with the fabric. Recent tests made in the Textile Section of the Bureau of Standards showed that more heat is transferred when the surface is painted black with lacquer than when it is polished. Presumably the surface of Mr. Freedman's calorimeter is polished, so that when it is covered with a thin fabric like No. 8 and No. 15 *more* heat is transferred in nominally still air than when the calorimeter is bare. Fabrics Nos. 12 and 13 perhaps would show a similar effect. Very likely if the surface of the calorimeter were blackened, more heat would be transferred by the bare calorimeter than when covered with any of the fabrics tested by Mr. Freedman.

Mr. Freedman indicates that the results obtained are not as reliable when the air is still as when the air is flowing. The question may be raised as to whether the thermal transmission with air flowing is as significant with respect to the use of fabrics as the thermal transmission measured in still air supplemented perhaps with measurements of the air permeability of the fabrics. It is believed that the results obtained with some of the previously reported methods are fully as significant as those reported by Mr. Freedman.

This does not detract from the value of Mr. Freedman's apparatus for studying the effect of air speeds on relative thermal transmission. The apparatus will no doubt prove to be useful in a number of ways. The fact that it is a self-contained unit requiring no auxiliary equipment makes it especially desirable.

MR. G. B. HAVEN.[1]—I wish to commend in the highest terms this admirably-drawn paper of Mr. Freedman's, and to express my appreciation of the great degree of use to which his apparatus can be put in the future. I know just how hard it is to write a paper such as this, because in 1918 it fell to my lot to measure the heat conductivity of a great many blankets. It was early in the period of the World War, and almost identical means with those of Mr. Freedman's were used in measuring the heat necessary to keep the temperature of a calorimeter up to the warmth of the human blood. Of course, our experiments were, in a measure, crude, since they were performed in still air. Two things caused us more or less difficulty in our experiments. One was the initial tension to be employed in winding on the specimen. I wish Mr. Freedman would tell us how this was adjusted in his tests. The other question was that of end leakage of heat, namely, at the ends of the calorimeter coil. I presume in the latter case that this was assumed to be a running loss and taken as constant. Upon such an assumption, it was probably disregarded. In the case of our tests, however, this assumption could not be made.

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[1] Professor of Machine Design, In Charge of Textile Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

It is interesting to note that if you take from Table V of the paper the proper insulation factor, as given by Mr. Freedman, the relation between a cotton and wool blanket for insulating properties is practically 83 per cent. This happens to be exactly the figure obtained in 1918 in our measurement of the insulating properties of these two classes of blankets. This confirms, in my mind, a very happy agreement in this kind of work, and shows the possibility of using tests like these extensively in the future.

MR. EPHRAIM FREEDMAN.[1]—Referring to the comments of Mr. Haven, the specimen under test was cut larger than the width of the calorimeter and also of greater length. It was placed around the calorimeter by hand. No tension was applied other than to take the two hack saw blades, which were shown in Fig. 2, and they were placed without any tension against the edges or ends of the material protruding from the blade. They form somewhat of a tail, and I believe help in directing the air flow, keeping the air from traveling around the calorimeter and directing it through the duct. The only tension that could be applied then would be due to the clamping together of the hack saw blades which would be negligible.

The end loss was considered as a running loss. We, however, wanted to find out just how much that amounted to, and while we have not continued with the experiments for lack of time we did place two additional pieces of asbestos board, one on top and one at the bottom of the calorimeter, and took additional readings of specimens which were previously tested. We found that the bare calorimeter required 2.33 watts per 1° F., as compared with 2.325 with single asbestos insulation.

(*By letter*).—Referring to Mr. Schiefer's comments, as Mr. Schiefer points out, an increase of 1.1° F. is observed while specimen No. 10 is under test. However, the temperature of the duct has also increased by 1.5° F., thus establishing a fairly constant relationship, for as shown in the last column of Table II, the actual difference amounts to only 0.002 watt per 1° F. Prolongation of test over a period of 90 minutes, and duplication of test on numerous occasions over a period of 7 months have served to corroborate the previous findings and conclusions.

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[1] Director, Macy Bureau of Standards, R. H. Macy and Co., Inc., New York City.

A series of experiments were conducted in order to ascertain the temperature of the air immediately surrounding various parts of the calorimeter as well as the temperature of the air at distant points (see the accompanying Table I) with 135 watts supplied to the calorimeter heater so as to magnify any possible temperature variations. The thermometers used were filled with mercury and were first calibrated against an A.S.T.M. thermometer and the observed readings were corrected accordingly. The thermometers were then arranged as follows: Thermometers Nos. 1 and 4 were placed at an angle of 180 deg. from the Bourdon spring thermometer (No. 5) and at points in close proximity to the outer surface of the calorimeter, No. 1 being farthest from No. 5 and No. 4 nearest it. Thermometers Nos. 2 and 3 were placed at right angles to Nos. 1 and 4, and at opposite sides to each other. Thermometer No. 6 was placed at a point equi-distant with No. 5 from the calorimeter but in the opposite direction.

TABLE I.—TEMPERATURE READINGS OF AIR SURROUNDING CALORIMETER WITH WIND VELOCITY AT 14.2 MILES PER HOUR.

Wattage	Immersion Depth of Thermometers, in.	Temperature, deg. Fahr.						Average of Thermometers Nos. 1, 2, 3 and 4, deg. Fahr.	Difference Between Thermometer No 5 and Average of Nos. 1, 2, 3 and 4, deg. Fahr.	Average of Thermometers Nos. 2, 3 and 4, deg. Fahr.	Difference Between Thermometer No. 5 and Average of Nos. 2, 3 and 4, deg. Fahr.
		Thermometer No. 1	Thermometer No. 2	Thermometer No. 3	Thermometer No. 4	Thermometer No. 5	Thermometer No. 6				
135	4	37.5	34.5	34.5	34.7	34.8	34.5	35.3	+0.6	34.6	−0.2
135	4	37.7	35.0	35.0	34.7	34.9	35.2	35.6	+0.7	34.9	0.0
135	4	38.3	35.0	35.0	34.6	35.0	36.0	35.7	+0.7	34.9	−0.1
135	4[a]	38.5	36.0	36.0	35.0	36.0	36.2	36.4	+0.4	35.7	−0.3
135	4[a]	39.3	36.3	36.3	36.2	36.2	37.2	37.0	+0.8	36.3	+0.1
None	4	34.4	34.1	34.1	34.4	34.4	34.2	....	...	....	...

[a] Thermometers Nos. 1 and 4 immersed to 9 in. depth.

A study of the table will disclose that the average of the readings of thermometers Nos. 1, 2, 3 and 4 differs between + 0.4 and + 0.8° F. from the readings of the Bourdon spring thermometer (No. 5). We find however that the average of the readings of thermometers Nos. 2, 3 and 4 which record the temperature of the air as it impinges on the specimen under test, differs from the readings obtained with thermometer No. 5 from − 0.3 to + 0.1° F., a difference of 0.4° F. A study of Fig. 3 will explain the reason for the different temperature readings of thermometers Nos. 1 and 6.

In the Leslie cube experiment,[1] one of the lateral faces of a brass cube is of polished metal, one is coated with lampblack, one with chalk or whiting while the fourth is of polished metal that has been varnished or lacquered. By the Leslie cube experiment it was proved that "bodies at the same temperature may differ greatly in radiating power," for it was found that . . . "the radiation from the lampblack surface is most energetic, that from the whitened surface is nearly as great, that from the varnished surface is less, while the polished metal surface gives off the least radiation." Remembering this experiment, the calorimeter wall was left unpolished. After 7 months of operation, check tests disclosed no change in radiating power of the calorimeter.

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[1] College Physics by Kimball, 1911, 1917.

Experiments conducted in still air (see the accompanying Table II), disclosed irregular temperature variations attributed to uncontrollable convection currents. In order to obtain results capable of duplication and taking into consideration that textile fabrics are more often subjected to flowing rather than still air, test with air flowing are considered more pertinent, especially since they also supply an index of the air permeability of the fabric.

TABLE II.—TEMPERATURE READINGS OF AIR SURROUNDING CALORIMETER WITH NOMINALLY STILL AIR.

Wattage	Immersion Depth of Thermometers, in.	Temperature, deg. Fahr.					
		Thermometer No. 1	Thermometer No. 2	Thermometer No. 3	Thermometer No. 4	Thermometer No. 5	Thermometer No. 6
35	4	47.1	40.0	40.0	40.1	37.2	38.2
35	4	38.3	46.0	47.0	41.9	42.3	43.0
35	4[a]	31.8	41.0	41.0	34.7	39.0	39.2
35	4[a]	33.6	43.5	44.0	36.3	40.4	40.7
35	4[a]	35.4	45.5	46.2	37.8	41.7	42.2

[a] Thermometers Nos. 1 and 4 immersed to 9 in. depth.

MR. R. H. MORRIS[1] (*by letter*).—I have found the paper by Mr. Freedman very interesting but was rather disappointed that he did not say more in his conclusion about what the tests show. Judging from the way the points on the right-hand side of Figs. 4 and 5 fall on a well-defined curve, I was wondering if one would be justified in assuming that the insulating properties of fabrics depended entirely upon the thickness of the cloth and are independent of the material of which it is made. For instance, Nos. 1 and 5 are almost identical so far as heat transmission is concerned, although one is wool and one is cotton.

When using the weight standard, that is, on the left-hand side of the same figures, this relation does not seem to be independent of the material. For instance, I am somewhat at a loss to account for materials Nos. 4 and 14, which have practically the same thermal transmission and yet No. 5, which is cotton, is only about half the weight of No. 14 which is wool. Evidently the weave or type of cloth has a great influence.

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[1] Associate Editor, *Power Plant Engineering*, Chicago, Ill.

After reading the paper I was very much interested in what Byrd had to say in his account of the trip to the South Pole. He favored the use of reindeer fur, although he stated that some polar bear clothes that he had were warmer, yet heavier. I wonder if you have made any further tests showing a comparison between the Alaska seal, No. 16 in your paper, with reindeer and polar bear furs.

MR. FREEDMAN (*author's closure by letter*).—In reply to Mr. Morris, while numerous tests other than those shown in the tables were conducted, the author did not care to disclose all of the information obtained at the time the paper was published. This information will be made available in due time, some of it will be released in the very near future.

Our experiences with materials under test indicate to us that one would not be justified in assuming that the insulating properties of fabrics depend entirely upon the thickness of the cloth. In Figs. 4 and 5 we chose various of the samples under test which would permit of a clearer picture when shown on a chart in the limited space allowed in the paper.

One will find that specimen No. 8 is thicker than specimen No. 1, yet it does not offer quite the thermal insulation of specimen No. 1 when tested in nominally still air. Specimen No. 14 is not quite as warm as specimen No. 9 when tested with wind velocity at 14.2 miles per hour. Numerous other cases of differences, in some cases very marked, were found. I agree that the weave and types of cloth have great influence on the thermal transmission of fabrics.

We have not yet made tests on reindeer cloths or polar bear furs. I am trying to assemble specimens of different types of fur coatings in order to conduct tests which I believe will be very interesting and enlightening to all concerned.

A MAGNETIC STRAIN GAGE

By J. Paul Shamberger[1]

Synopsis

For a long time there has existed a need for an instrument that would determine stress accurately in mechanical structures, not only under static but also under dynamic conditions. The Westinghouse Electric and Manufacturing Co. has recently developed such an instrument which is termed a magnetic strain gage, a description of which is given in this paper. This gage can be used for measuring strain and therefore determining stress under dynamic conditions in such structures as railroad rails, locomotive side rods, bridge members, shafts, wheels and many other structures. It is equally adapted for determining stress under static conditions in the laboratory or in the field. The gage is simple in construction and rugged and requires no delicate handling, yet possesses a high degree of sensitivity and accuracy.

The measuring of small mechanical displacements, such as the strain in metals, has been performed under static conditions with a good degree of accuracy for a number of years. The measuring of strain under dynamic conditions, however, has always been very difficult. Delicate instruments suitable for laboratory use will not withstand the vibration and shock of machine members. Furthermore, the design of most laboratory instruments is such that their readings cannot be recorded when the instrument itself is in motion as it would be on a revolving wheel. An electrical instrument embodying some very desirable characteristics and suitable for measuring strain either under static or dynamic conditions has recently been developed by the Westinghouse Electric and Manufacturing Co. This instrument was conceived and designed by J. G. Ritter, Engineer, Railway Equipment Engineering Department of the company.

The Gage

To date, the most extensive application has been to measure the stress produced by locomotives in railroad rails. In Fig. 1 are shown the separate parts of a gage designed for this application. In Fig. 2 are shown the working parts of this gage assembled and in Fig. 3 is shown the gage complete with cover. The electric circuit is shown

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[1] Engineer, Railway Equipment Engineering Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

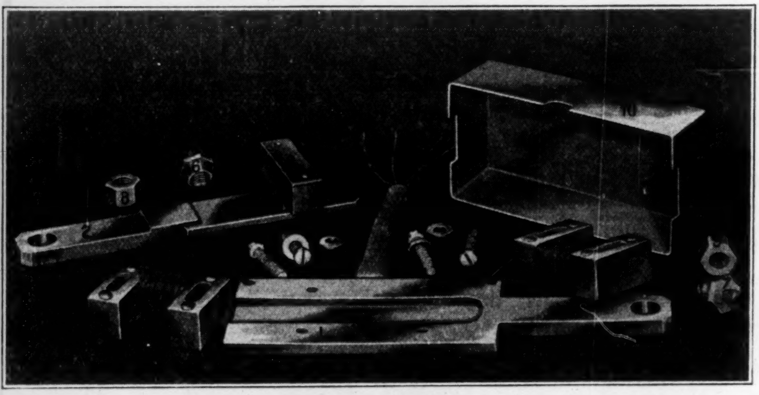

FIG. 1.—Separate Parts of Magnetic Gage.

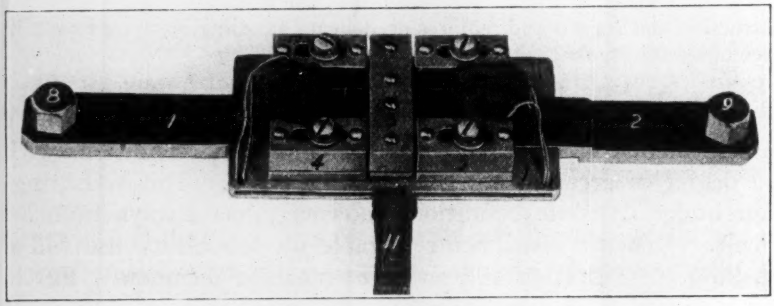

FIG. 2.—Working Parts of Magnetic Gage Assembled.

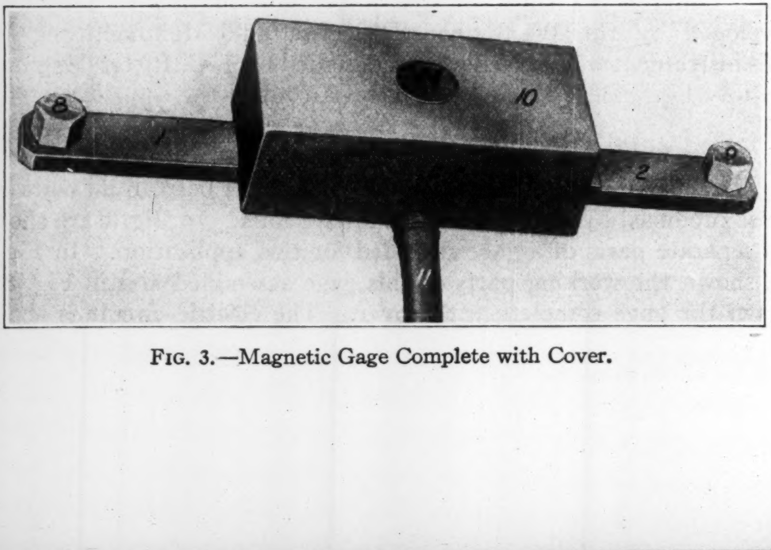

FIG. 3.—Magnetic Gage Complete with Cover.

in Figs. 4 and 5. The gage depends for its operation upon the change in the reluctance of two magnetic circuits as an armature is moved in an air gap.

Using the numerals shown in Fig. 1, the gage consists essentially of a base *1*, a slide, *2*, an armature, *3*, and two reactors *4* and *5*. These parts are combined so as to form, in reality, two pieces as shown in Fig. 2. The two reactors are fastened to the base forming one piece, and the armature is fastened to the slide thus forming a second piece. The slide is connected to the base by means of a cross-head guide.

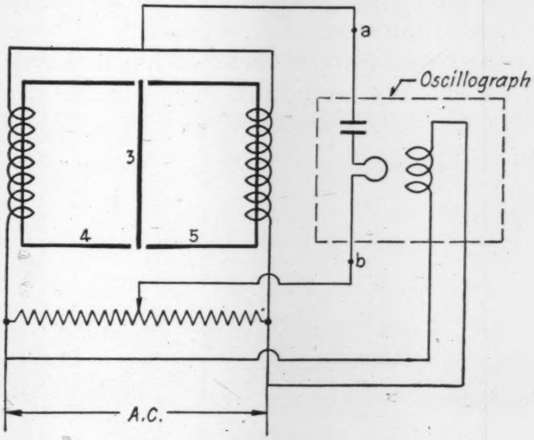

FIG. 4.—Electric Circuit for Dynamic Testing.

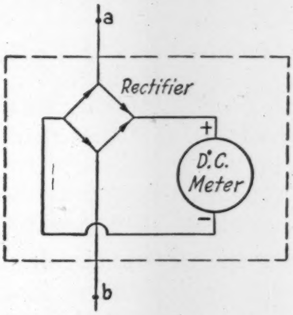

FIG. 5.—Electric Circuit for Static Testing.

The operation of the gage can be seen from Fig. 2. The armature moves in the air gap formed between the two reactors. As it moves from one reactor to the other, the voltage across the coil of one reactor increases while that across the coil of the other reactor decreases. It is this change in voltage that is recorded.

The method of fastening the gage to the test specimen is shown in Fig. 6, although this figure does not represent a specimen. The two studs are fastened to the specimen at gage length distance. The base *1* is then fastened to one stud and the slide *2* is fastened to the other. When the specimen is subjected to strain the distance between the two studs is changed, thereby displacing the armature *3* in the air gap. This displacement of the armature in the air gap causes the electric current through the recording instrument to be varied in proportion to the magnitude of the strain.

Cone-shaped studs, pieces *6* and *7* of Fig. 1, have been found to be the most satisfactory method of fastening the gage to the test specimen. Other methods of fastening, such as a knife edge, could be used for certain kinds of testing if desired. The gage here illustrated has a gage length of 8 in.

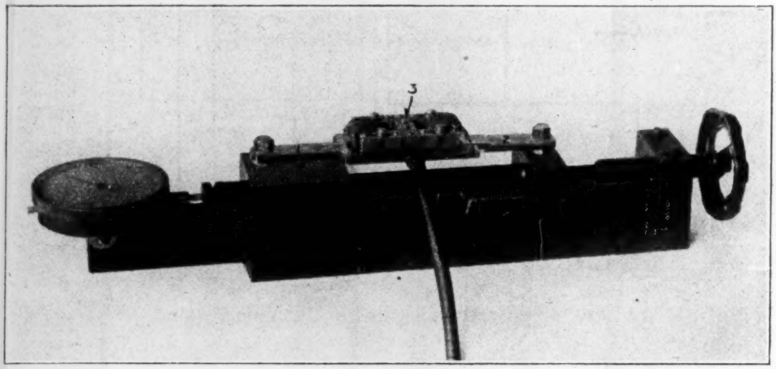

FIG. 6.—Calibration of Gage.

THE ELECTRIC CIRCUIT

For dynamic testing the electric circuit shown in Fig. 4 has been used. This arrangement employs an oscillograph having a damped element and an alternating current field. A condenser is placed in series with the oscillograph element for the purpose of bringing the magnetic flux from the element in phase with the magnetic flux from its field. The element is damped in order to make the record on the film a line rather than an envelope. The width of the line depends upon the amount of damping; the greater the amount of damping the narrower the line. The amount of permissible damping depends upon the frequency of the dynamic changes being measured. For low-frequency dynamic changes the amount of damping may be rather large before the element fails to follow the changes accurately. For rapid dynamic changes the amount of damping should be small or perhaps none at all, depending upon the rapidity of the changes. The rapidity of the dynamic changes also determines the frequency of the applied voltage to the gage. A frequency of 750 cycles per second has been found entirely satisfactory for the dynamic tests that have so far been made.

For static testing, the copper oxide rectifier and direct current milliammeter of Fig. 5 may be substituted for the oscillograph of Fig. 4. This makes a simple arrangement and has proved to be very satisfactory. It is possible to use a frequency of 60 cycles for static testing, but a higher frequency is more desirable as it permits using a smaller gage.

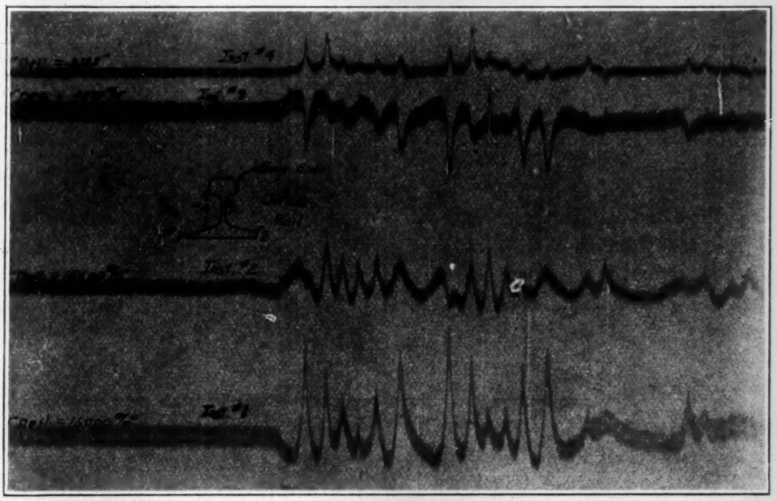

FIG. 7.—Typical Oscillograph Record in Test of Railroad Rail.

CALIBRATION

The gage can very easily be calibrated by using a device such as that illustrated in Fig. 6. A dial gage is used to indicate the displacement of the armature in the air gap and for dynamic testing the calibration record is made directly on the oscillograph film. For static testing the calibration is obtained from the direct current milliammeter.

AUXILIARY APPARATUS

In addition to the magnetic gage a certain amount of other apparatus is necessary for test work. For dynamic testing some sort of high-frequency power is required. This is most conveniently obtained from a motor-generator set that can be operated from a 25 or 60-cycle power line or from an independent source of power such as a farm lighting outfit. The power requirement for the arrangement shown in Fig. 4 is about 140 watts for each gage. Most of this power is consumed in the oscillograph field. For this reason the power requirement for the arrangement shown in Fig. 5 is very much less—about 6 watts for each gage.

For dynamic testing the essential auxiliary apparatus consists of: A high frequency motor-generator set, an oscillograph, a small potentiometer (10 ohms, 1 ampere), a gage calibrating device and necessary controls. For static testing with high-frequency current the oscillograph is replaced by a copper oxide rectifier and a direct current milliammeter, as mentioned previously.

RECORDS THAT CAN BE OBTAINED

In Fig. 7 is shown a typical oscillograph record of conditions produced in a 130-lb. Pennsylvania standard railroad rail by an electric locomotive on a 10-deg. curve. The location of the gages on the rail, also the wheel arrangement of the locomotive is shown in the figure. It will be noticed that No. 4 gage does not record strain directly but rather distortion between the head and the base of the rail.

From the records of Fig. 7, it is possible to determine the vertical and lateral forces acting on the rail. This is done by means of a calibration which utilizes the rail as a spring scale. Under static conditions, known vertical and lateral forces are applied to the rail and all gage displacements recorded, thus obtaining the relation between gage displacements and forces. From the dynamic records with their known displacements the unknown forces can then be determined from the calibration.

The gage calibrations shown in Fig. 7 by no means represent the limit of sensitivity for the gage. The highest sensitivity shown is 4070 lb. per sq. in. average stress over a length of 8 in. for a deflection of 1 in. on the oscillograph film. This sensitivity could have been greatly increased if higher sensitivity had been desired. There are a number of factors influencing sensitivity that must be considered in the design and operation of the gage.

APPLICATIONS

The applications that have already been made are:

1. The determination of stress under dynamic conditions in rail-

road rails, locomotive rods and laboratory test specimens (vibration).

2. The determination of stress under static conditions in railroad rails and laboratory test specimens.

Several applications that are contemplated in the near future are:

1. The determination of stress under dynamic conditions in railroad track splice bars, splice bar bolts, oil-drilling machinery and various members of bridges.

2. The adaptation of the gage as a caliper or micrometer for checking the variation in dimensions of factory-machined pieces that are manufactured to small tolerences.

The gage that will be used on railroad track splice bars and splice bar bolts will have a gage length of 4 in. and will be much smaller in all other respects than the 8-in. gage illustrated.

In general this instrument can be applied for measuring strain, or any linear displacement of similar magnitude, either under static or dynamic conditions, wherever the requirements as regards the weight of the instrument itself and the inertia of its parts are not exceedingly critical. For the laboratory vibration test the instrument weight was made low by building the instrument small and by constructing all parts, except the armature and reactor cores, from aluminum.

CONCLUSION

The outstanding characteristics of this gage are simplicity, ruggedness and sensitivity. It requires no delicate handling and this feature is much appreciated in field work. Gage length, size of gage and sensitivity can be varied over a wide range, thus making it adaptable to a large variety of applications. It is equally adapted for use in the laboratory or in the field under either static or dynamic conditions. Its ruggedness is the feature that makes it particularly suitable for dynamic testing and it is its ruggedness that resists the chattering and vibration of such structures as railroad rails and locomotive rods. It is believed that this gage will fill a long-felt need and will find many useful applications.

DISCUSSION

Mr. A. N. Talbot[1] (*presented in written form*).—The magnetic strain gage described by Mr. Shamberger has qualities and characteristics which seem to make it applicable to measurement in a variety of strain testing work, particularly under dynamic loading of the specimen or member tested. The records which have been obtained in the tests made by the staff of the Westinghouse Electric and Manufacturing Co. show a high degree of definiteness and accuracy. The form of the instrument may be changed to suit a variety of conditions. It is planned to use the newer form of instrument referred to in the paper for the tests on rail and rail joints to be made under a wide range of train speeds the coming season in the investigations of the Joint Committee on Stresses in Railroad Track. The magnetic strain gage seems destined to become a valuable tool in many lines of strain measuring work.

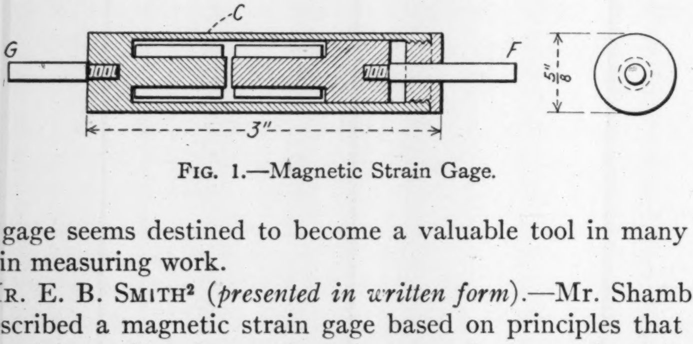

Fig. 1.—Magnetic Strain Gage.

Mr. E. B. Smith[2] (*presented in written form*).—Mr. Shamberger has described a magnetic strain gage based on principles that have been used in various forms of strain gages for a number of years. About four years ago I constructed several gages using two electromagnets almost identical with those described, but several mechanical difficulties inherent in such a construction led to a more compact and easily manufactured strain gage. The form of this magnetic strain gage which was first used in the summer of 1926 is shown in the accompanying Fig. 1. It consists of a cylindrical iron shell, *C*, and two pole pieces with windings inside. One magnet is fixed to the shell and the other slides freely, but in contact, within the shell. The gage bars *F* and *G* may be made of any convenient length.

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[1] Professor Emeritus, University of Illinois, Urbana, Ill.

[2] Research Professor of Mechanical Engineering, Iowa State College, Ames, Iowa.

The two magnetic coils are so proportioned in ampere-turns that there is a maximum inductive effect between them when an alternating current is flowing in one of them. In operation, a constant alternating current value is maintained in one coil which induces a current in the second coil depending upon the magnetic gap between the ends of the pole pieces. The indication may be by the use of a milivolt meter or by records from an oscillograph.

This instrument has been used for the direct measurement of deformations in materials. Its sensitivity gives accurate reading to 0.00001 in. The range, however, of all such instruments operating on the principle of the variation of a magnetic gap is rather limited. There is an approximate straight line relation between gap and induced current up to about 0.01 in.; beyond this limit there is a decided curve in the calibration line.

The current used in this gage for the measurement of static deformations was 60 cycle, 110 volts. It works satisfactorily on other frequencies but must have a calibration curve for each frequency and voltage value.

This same principle has been used successfully in a small soil pressure cell about 1½ in. in diameter and ½ in. thick.

MR. B. F. LANGER[1] (*by letter*).—The value of the ability to measure small, rapid motions in experimental and research engineering work can hardly be over-estimated. Our Research Laboratories are applying this same magnetic principle in the study of vibrations and accelerations. Instruments of this type can be placed in inaccessible parts of locomotives, for example, to study not only stresses but vibrations and accelerations of the moving parts. Current from the instrument can be taken out through slip rings if it is located on a rotating part. The electrical power supply can be obtained from the locomotive itself, if it is electric, or from a coach in the train if it is steam.

Heretofore, the best instrument available for similar work was the Peters carbon-pile telemeter. The telemeter will always be useful where the electrical power supply is difficult to obtain and where the vibrations are not excessive. The fact that it can operate from a storage battery is a great advantage for some applications. The magnetic gage, however, is more rugged and not affected by vibration of the member to which it is attached. The working parts can be made smaller and can more easily be adapted to special applications where space is a limiting factor. It can readily be adjusted to measure either extremely small displacements of around 0.0001 in.

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[1] Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

or comparatively large ones up to about 0.05 in. without mechanical amplification or reduction. The standard telemeter strain gage has to use a mechanical reduction of the motion which makes the gage larger, more expensive, and more apt to vibrate at its own natural frequency when subjected to shock. The natural frequency of the magnetic gage is so high that it need not be considered.

MR. A. V. DE FOREST.[1]—This instrument draws attention to the class to which it belongs. The use of a variable electric current, produced by a small motion of a diaphram, was the origin of the telephone. In the strain gage manifestations we have, as in the telephone, the variable resistance type, the variable induction type, and the varying capacity type. All three of them fit particularly well in various fields. The Peters telemeter constitutes the resistance type, which works in a very similar manner to this inductive instrument. The variable condenser type of measurement using high frequencies and measuring small motions has been called the ultramicrometer. The parts may be made very small and light and are adapted to many kinds of laboratory measurement.

For many purposes, particularly where comparatively large displacements of the order of thousandths or tenths of inches are involved, the variable induction system is the most convenient. I have used extensometers of this type for wire and general testing machine use for a number of years. It is easily possible to plot stress-strain diagrams using a high degree of sensitivity below the elastic limit, and a second scale such that the whole elongation can be recorded on a second coarser scale. The extensometer is sufficiently rugged to leave in place till the specimen is broken.

There is an unlimited field for the use of electric measurements of displacement, particularly since the vacuum tube has opened up the field to almost unlimited sensitivity. The author is to be thanked for a well designed application of this type of instrument.

MR. H. F. MOORE.[2]—I would add a comment to the discussion of this very ingenious instrument and new tool for the delicate measurement of strain, not in any sense in a critical frame of mind, but merely by calling attention to the use of this type of instrument, also to the variable resistance and the variable condenser type, and point out that if it is necessary to take very large numbers of determinations, an instrument in which it is necessary to develop a photographic film before you can tell whether your results are any good or not, has certain drawbacks which sometimes operate in favor of a more direct mechanical instrument of less sensitivity and greater rapidity of action. In studying the stresses in rails, for a good many years a direct instrument recording upon very lightly smoked glass has been used. Readings to a sensitivity of 0.0001 in. can be obtained with fair regularity and records are made with extreme rapidity and checked with a field microscope, as they are made, so that the work can be corrected on the spot. I am not bringing this up as a criticism of the instrument described in this paper, except to note that if you have to go to the sensitivity of the oscillograph, you must be willing to pay the price in the bother of having to develop a film before you know what your records are, and in increased slowness of obtaining results. It is just a question of what sensitivity you need in your tests and what you are willing to pay for it.

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[1] Consulting Engineer, American Chain Co., Inc., Bridgeport, Conn.

[2] Professor of Engineering Materials, University of Illinois, Urbana, Ill.

MR. CHARLES JABLOW.[1]—I should like to call to Mr. Moore's attention the fact that while the difficulty he mentions admittedly exists, I do not believe it is quite as bad as he really imagines. The development of our photographic film was not a very difficult task, and frequently within ten minutes after the train had gone by, we were examining our film to see just what it looked like, and we had a completely developed film. It is just a question of drying, so I do not believe that the slowness factor was so very difficult, and then of course we have indelible records for all time that we can study at a later time.

One point Mr. Moore did bring out, and it certainly is admittedly a weakness of the scheme, is the auxiliary apparatus. I might say, however, that, on that score, it is true that when we are talking about the multiplicity of gages, the auxiliary apparatus does have to have some size and some weight on account of the motor generator sets involved. However, our company is now developing a very light portable high frequency motor generator set, that can be carried from place to place by man power instead of some other kind of power, and will probably take care of about three gages.

MR. F. G. TATNALL.[2]—We have for years been working on this same problem using the Peters resistance apparatus. The main difference between the Peters apparatus and that of Westinghouse is that we work with direct current with a maximum of six volts, whereas Westinghouse employs high frequency alternating current, both methods using an oscillograph.

In 1928, we made tests for the American Railway Engineering Association under the auspices of the Pennsylvania Railroad on stress in track and joint bar bolts during the operation of fast trains and heavy-duty freight trains.[1] These tests developed the fact of maximum increase in stress occurring under smaller diameter wheels in the following order: tank wheels, pilot wheels, trailer wheels, and driving wheels, and increased as the speed of the moving load increased. From the tests reported using the strain gage described in the paper, it appears that the driving wheels produce maximum stress.

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[2] Manager, Testing Equipment Division, Southwark Foundry and Machine Co., Philadelphia, Pa.

Our tests show that under high train speeds the frequency of vibration varied between 400 and 500 cycles per second. The natural frequency of the instrument did not enter into consideration here as it was attached rigidly to the steel member under test and was caused to suffer forced vibration. With the magnetic strain gage where a motor generator set is used, this set would have to produce a frequency considerably higher than 500 cycles per second to record this forced vibration.

In general, there are fundamental stress waves with high frequency waves superimposed upon them, although the peaks of stress come from the algebraic sum of the two.

Both direct current and alternating current methods of measuring dynamic stresses are in their infancy and, in developing side by side, interesting comparisons are available. As Mr. Moore states, each has the apparent disadvantage of taking its record with an oscillograph wherein it is necessary to develop the film before the record is available. The best way of course would be to have the picture appear directly on a viewing screen. This is now possible in repeated phenomena but not in transient stress measurement. The nearest approach is the cathode-ray oscillograph, but the use of the latter is limited in this work for many reasons.

MR. D. D. MCGUIRE.[2]—I should like to call your attention to another piece of apparatus illustrated in the *Engineering News-Record* of August, 1926. This is a strain gage almost exactly like the one just explained except that it is more simple.

MR. J. PAUL SHAMBERGER[3] (*author's closure by letter*).—The gage described by Mr. McGuire in the *Engineering News-Record* for August, 1926, and which he states is almost exactly like the magnetic strain gage, has been carefully studied. It is found that Mr. McGuire's gage is different mechanically, electrically and magnetically from the magnetic strain gage.

Mr. Smith states that about four years ago he constructed several gages using electro-magnets almost identical with those described but because of mechanical difficulties he changed his design. The magnetic strain gage using the type of electro-magnets described in the paper has been used within our own organization since 1923. We have met no insurmountable difficulties in building this gage but have found its mechanical construction very satisfactory and have been able to design it in a variety of forms, one form being a small cylinder.

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[1] *Bulletin*, Am. Railway Engineering Assn., Vol. 31, No. 324, February, 1930, p. 1556.

[2] District Engineer, National Sand and Gravel Assn., St. Louis, Mo.

[3] Engineer, Railway Equipment Engineering Department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

It was not the intention to discuss, in this paper, the general problem of stress in railroad track. However, because of Mr. Tatnall's remarks it will be necessary to make certain comments.

Mr. Tatnall states that (1) the stress in railroad track depends upon the diameter of the wheel producing the stress, (2) that the stress in track bolts under a dynamic load varies with a frequency of about 500 cycles per second, and (3) that a frequency of 750 cycles on the magnetic strain gage is not sufficiently high to record a 500-cycle frequency change in stress.

Numerous analytical studies and many experiments have shown that the bending stress in railroad track, so far as the rolling equipment is concerned, depends upon (*a*) wheel loads (vertical and lateral) and (*b*) wheel spacings. Wheel spacings are important because of reverse bending. Purely bending stress is independent of wheel diameter.

An analysis indicates that the natural frequency of a track bolt is very much higher than 500 cycles per second. Analysis also indicates that the natural frequency of the track rail is quite different from that of the track bolt. Any forced frequency in the bolt must be produced by the rail since the wheels come into contact only with the rail. The question, then, naturally arises, "How can the rail with one frequency maintain vibrations in the bolt at an entirely different frequency?"

In the German publication "Der Stahlbau," 1928, Heft 13, there is an article by Rudolf Bernhard entitled "Beitrag zur Brückenmesstechnik." In this article Bernhard describes some bridge tests he made with a telemeter. In all his records he found a 500-cycle frequency. He then investigated the telemeter and found that it possessed, when clamped to a specimen, a natural internal frequency identical with that which he had found on his films, that is 500 cycles.

It is extremely improbable that such widely different structures as (1) a bridge (in Germany) and (2) a track bolt (in America) should both have identically the same natural frequency of vibration. The inference, then, is that the 500-cycle frequency wave interpreted as track bolt stress was, in reality, not produced by stress but rather by the internal natural frequency of the telemeter.

A frequency of 750 cycles impressed on the magnetic strain gage appears as a frequency of 1500 cycles on the film. It is believed that a frequency of 1500 cycles is sufficiently high to detect a variation of 500 cycles per second if such a variation exists.